FHWA/IN/JTRP-2006/40

Final Report

IMPLEMENTATION OF HEALTH MONITORING PROCEDURES FOR ITS SENSORS

Volume 1: Research Report

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June 2008

TECHNICAL *Summary*

Technology Transfer and Project Implementation Information

INDOT Research

TRB Subject Code: 54-9 Traffic Control Device Procedures and Performance Measures *June 2008*
Publication No.: FHWA/IN/JTRP-2006/40, SPR-3026 *Final Report*

Health Monitoring Procedures for Freeway Traffic Sensors
Volume 1: Research Report

Introduction

INDOT has deployed several ITS traffic monitoring stations in Northwest Indiana and in the greater Indianapolis area. These sensors provide vital information regarding traffic conditions that the corresponding traffic management centers (TMCs) use to determine when incidents occur, where they are located, and severity of traffic impact. After the incident is cleared these stations are used to determine when advisory messages to the public should be removed.

Sensor health monitoring test procedures need to be established and implemented so that TMCs are provided with daily or weekly reports with prioritized lists identifying specific sensors that are providing suspect data. Based upon this prioritize report, technicians will be dispatched to inspect, retune, or perhaps schedule replacement. Depending upon the condition of the sensor, these sensors may also be removed from the TMC decision making process.

Findings

Using the DMAIC Performance Improvement Procedure, previously applied to Weight in Motion sensor data quality control, can improve the confidence with which the Traffic Management Centers use freeway sensor data.

The DMAIC process, which has its origin in manufacturing, has been applied in the context of freeway sensors, with an emphasis on the Analyze, Improve and Control steps of the procedure. Data was collect from a test location on I-65 (near milemarker 128) at an existing ATMS sensor and communications site. Two additional sidefire radar sensors were added to the site to supplement the existing Microloops. Groundtruthing of the data was accomplished by post event analyzing using video collected from existing traffic monitoring cameras. Sensor performance metrics were analyzed for all sensors and were used in the test-bed health monitoring.

Analysis of several case studies of the use of the Average Effective Vehicle Length metric showed that while it is not a perfect metric that it can be used to detect suspect sensor malfunctions. It was also found that each traffic lane has different characteristics that can be used to narrow the upper and lower AEVL limits. A procedure was developed to allow the historical data from sites to be used in a manner that provides a better indication of sensor data quality issues.

Implementation

Work with INDOT system integrator to incorporate the calculation of Average Effective Vehicle Length (AEVL) [Equation 3.3] into the INDOT data archiving infrastructure for specified time intervals during the day.

Work with INDOT system integrator to retrieve and archive sensor occupancy to at least one decimal place [Table 6.2].

Using the calculated AEVL, develop triaging protocol for identifying sensors most in need of maintenance [Section 9.3, Figures 9.2 and 9.4] and corresponding field procedures such as field inspection and temporary co-located sensors [Figure 3.2 and 3.4].

Construct a portable side-fire sensor device with data collection capabilities [Figure 4.4, 4.5, Table 6.3] for identifying conditions [Figure 8.5] that are causing sensor errors.

Formalize contract acceptance procedures to ensure systematic installation errors do not occur. (Troy Boyd has already initiated this by requiring vendors to document performance on one site, before authorizing payment on subsequent sites).

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HEALTH MONITORING PROCEDURES FOR FREEWAY TRAFFIC SENSORS

Volume 1: Research Report

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Project No. C-36-75P
File No. 8-9-61
SPR-3026

Conducted in Cooperation with the
Indiana Department of Transportation
and the
U.S. Department of Transportation
Federal Highway Administration

Purdue University
West Lafayette, IN 47907
June 2008

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/IN/JTRP-2006/40	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Health Monitoring Procedures for Freeway Traffic Sensors, Volume 1: Research Report		**5. Report Date** June 2008
		6. Performing Organization Code
7. Author(s) Timothy J. Wells, Edward J. Smaglik, and Darcy M. Bullock		**8. Performing Organization Report No.** FHWA/IN/JTRP-2006/40
9. Performing Organization Name and Address Joint Transportation Research Program School of Civil Engineering Purdue University West Lafayette, IN 47907-2051		**10. Work Unit No.**
		11. Contract or Grant No. SPR-3026
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

An important component of any ITS system is the network of sensors used to monitor the traffic performance throughout the freeway system. These freeway sensors are used to alert Traffic Management Center (TMC) dispatchers to incidents and to predict travel times for roadway users. Data quality is essential to maintain peak TMC operational efficiency and to maintain the public's confidence in the information. The large number of sensors and data produced on a daily basis makes the use of human groundtruthing nearly impossible. Therefore an automated ongoing sensor data quality monitoring process must be implemented to identify the sensors in most need of attention.

This project proposes a system-wide heuristic approach to station health monitoring based on the principles of the "Six Sigma Process" and DMAIC Model for error identification and control. A test location on I-65 was outfitted with three different sensors; two side-fire radar sensors and 3M Microloop sensors. Data was collected and analyzed to assess the quality of sensor data, using performance metrics based on volume, speed, occupancy and Average Effective Vehicle Length comparison.

This study recommends combining sensor outputs into the single Average Effective Vehicle Length (AEVL) metric. Combined with the use of historical values and heuristic site knowledge the AEVL metric can provide a good tool for initial data quality control monitoring. Additional control efforts involve the use of portable side-fire radar units for temporary sensor co-location.

17. Key Words Sensor Data Quality, Sensors, Performance Metrics, Average Effective Vehicle Length, Sensor Co-Location	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	290	

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IMPLEMENTATION REPORT

- Work with INDOT system integrator to incorporate the calculation of Average Effective Vehicle Length (AEVL) [Equation 3.3] into the INDOT data archiving infrastructure for specified time intervals during the day.

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- Formalize contract acceptance procedures to ensure systematic installation errors do not occur. (Troy Boyd has already initiated this by requiring vendors to document performance on one site, before authorizing payment on subsequent sites).

CHAPTER 1. INTRODUCTION

1.1. ITS Data Challenge

The effectiveness of any system is based on how well it performs the tasks for which it was built. The modern Advanced Traffic Management System used by the Indiana Department of Transportation for Freeway Traffic Management is no exception. Furthermore the ATMS as a whole is composed of subsystems which are subject to similar Measures of Effectiveness (MOE's). The subsystem, which is the subject of this research project is the freeway sensor system that provides data to the Traffic Management Centers. The challenge facing those responsible for deployment and maintenance of freeway sensor equipment is to determine which sites are providing data of acceptable quality and which sites need some sort of maintenance or calibration.

The typical ITS site provides data to the Traffic Management Center (TMC) in the form of interval volume, interval average speed, and interval occupancy. The typical interval length is 30 seconds and the typical site reports these values for all lanes. Current plans call for more than 200 ITS sensors sites to be deployed throughout the INDOT freeway network for use in Traffic Management, with the likelihood that any additional roadways or reconstructed sections will include additional ITS sensors. Since ITS data is provided on a lane by lane basis, and assuming an average of six lanes of traffic for each sensor site, the number of lanes for which data is being collected is likely to exceed 1200. In the near future the number of 30 second ITS data records collected will exceed 3.4 million daily. Thus the amount of information provided by the typical freeway sensor site compounded by the fact that hundreds of such sites are part of the system leads to the conclusion that a procedure is necessary to assist determining when sensor data is suspect.

1.2. Public Access to Data

The public is the end user of any Intelligent Transportation System and will ultimately have a role in deciding the success or failure of any Advanced Traveler Information System. ATIS systems rely heavily on traffic sensors to provide information to the TMC. This information is then relayed to motorists through a variety of media which results in some shifting of demand from affected roadways to non-affected roadways. Information is made available to the public in several ways, as shown in Table 1.1.

Table 1.1 INDOT's ATIS Information Transfer to Public (1)

Technologies	**Deployment**
Dynamic Message Signs	46 Overhead 20 Portable
Highway Advisory Radio AM 530, AM 1610	23 stations statewide, 2.5 mile radius for coverage
Internet Access	TrafficWise.org
E-mail notification	Limited to INDOT Users
Alphanumeric Pagers	Limited to INDOT Users

An example of a Dynamic Message Sign (DMS) is shown in Figure 1.1. Dynamic Message Signs are used to provide relevant information to motorists with respect to downstream roadway restrictions thus providing the opportunity for re-routing vehicles and decreasing motorist delay and user cost.

Figure 1.1 I-65 Example of Dynamic Message Sign on I-65 north of Zionsville, IN

The use of freeway traffic sensors for predicting travel times also plays an important role in route selection and possible switching to alternate routes. Travel time prediction will rely heavily on freeway traffic sensor data and automation to provide relevant and real-time data. The public perception of travel times and their relevance will rely on how accurately the freeway sensors are providing data. Poor data quality can lead to erroneous travel times and degradation of the public trust in the ATIS system as a whole.

1.3. Six Sigma Process – DMAIC

The Six-Sigma process control model has been successfully used by companies interested in improving the repeatability of production and reducing customer complaints. A systematic approach to implementing Six-Sigma is the DMAIC model (2,3,4), which provides a step by step procedural context for determining the root cause of defects and preventing them in the future. This model, applied to the context of freeway sensor data is shown in Figure 1.2 (5). Decreased defects in production are indispensable in reducing the marginal cost of production and boosting profitability. The desire is to produce the greatest number of units with the least number of defective units. The Six-Sigma Process goal is to provide the manufacturer with one defective unit for one billion units produced. Although Six Sigma quality is probably not feasible for highway sensors, the concepts are directly applicable.

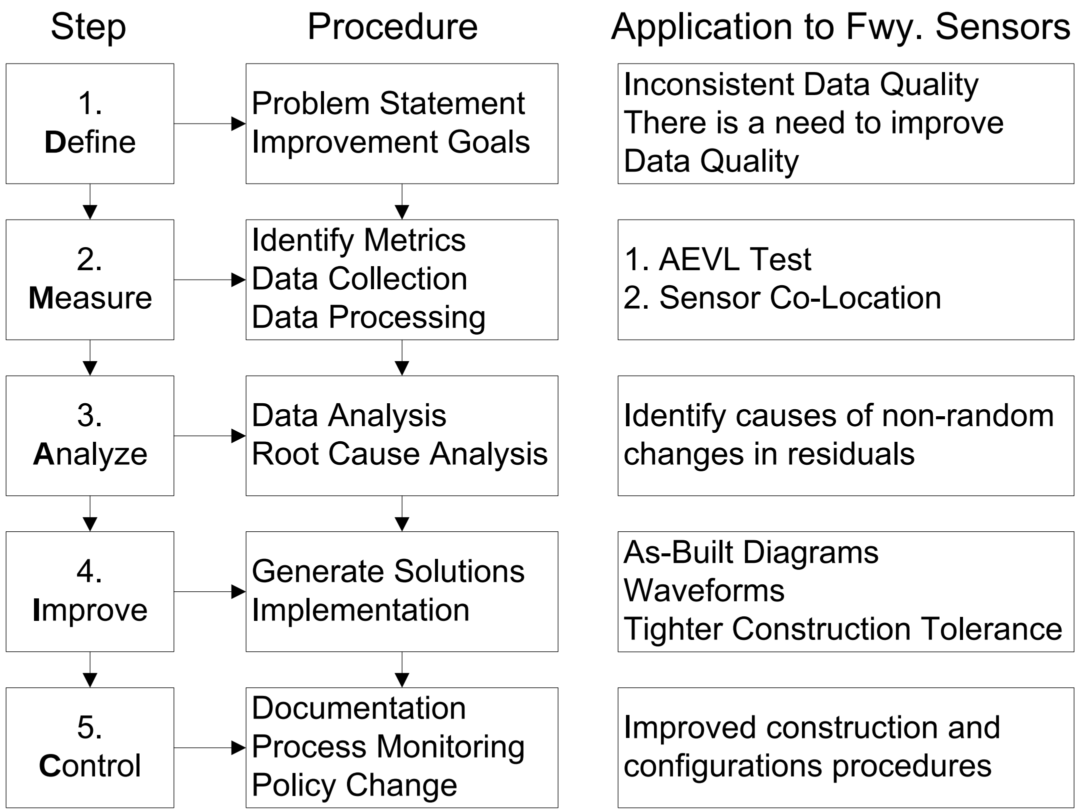


Figure 1.2 DMAIC Performance Improvement Model (5)

1.3.1. Define

The define step of the DMAIC model involves the formulation of a problem statement and outlines goal for improvement. In the context of a Freeway Traffic Sensor, the desired output is high quality data which can be used by the INDOT

Traffic Management Centers. The objective of this research is to provide an implementation procedure for the ongoing monitoring of Freeway Traffic Sensor Data.

1.3.2. Measure

The measurement step involves developing ways to evaluate data quality based on the used of inherent properties of the data itself. Data collection and processing are also included in this step. Performance metrics relating to quality monitoring for this project are as follows:

- Volume vs. Time
- Average Speed vs. Time
- Cumulative Sensor ‘On-Time’ vs. Time
- Average Effective Vehicle Length vs. Time

These performance metrics are covered in detail in Chapter 3.

1.3.3. Analyze

The third step in the process is to analyze the processed data. This step involves uncovering trends in the sensor data. Trending is important since the desire with the DMAIC process is to determine the root cause of data quality problems. The determination of error causality is indispensable to control the process and reduce error occurrence.

1.3.4. Improve

The fourth step in the process is to generate and implement solutions at the lowest level to prevent future quality issues. For example, making sure that the construction process is checked for compliance with specifications prior to acceptance and that the data quality meets acceptable levels. This involves implementing procedures to address the root causes of error occurrence determined from the analysis.

1.3.5. Control

The final step of the DMAIC process is to assess the output from the process and determine if the required level of quality has been achieved. In the case of freeway sensor data the process is ongoing due to the need for constant sensor monitoring, as traffic characteristics and flow are dynamic. Therefore the process becomes iterative and returns to a previous step in the process and further root causes of error are determined and corrective actions are taken to mitigate them. For ITS sensors the root causes of error can be categorized into two steps: Pre-Deployment and Post Deployment of the sensors.

1.3.5.1. Pre Deployment of ITS Sensors

In the sensor pre-deployment stage preventative action can be taken to ensure that the contractor and transportation agency are working towards the same goal of high quality data.

1.3.5.1.1. Construction Specifications

The need for explicitly clear construction specifications is evident when referring to ITS sensors, since even small deviations from the manufacturer's specifications can result in unacceptable levels of data quality. The use of contract special provisions and payment milestones using performance based specifications can improve data quality. An example of innovative construction specifications involves the usage of a sequential performance based specification. This technique requires the contractor to provide an initial sensor location which must meet data quality control levels prior to proceeding with multiple locations. This technique was recently used by INDOT on the Indianapolis ITS Deployment (Phase Three) Project.

1.3.5.1.2. Construction Quality Control (Inspection)

Construction inspection is critical to ensure contractor compliance with project plans and specifications. Frequent inspection increases the likelihood that potential problems will be discovered early in the construction process. Early detection of potential problems enables communication to be established with the contractor that can minimize potential legal disputes. Items necessary for inspection include:

- Sensor Depth
- Cable Splice Quality
- Sensor Alignment with Lane
- Conduit Horizontal Separation (for Microloop Speed Traps)
- Side-fire Radar Location with respect to potential obstructions

1.3.5.1.3. Sensor Specifications (Data Quality Control)

Clearly defining the minimum level of performance required from ITS sensors is crucial to a successful outcome for all parties of the process. A contractor must know that unlike a typical construction project that is based on producing an object for use, sensors are only installed for the data they produce. Failure to produce acceptable data, as defined in the sensor specifications section of the contract documents is unacceptable and could lead to the need to completely reinstall affected sensor infrastructure. Knowledge of this criterion by the contractor can prevent litigation and contract disputes.

1.3.5.2. Post Deployment of ITS Sensors

After the sensors are deployed in the field and the calibration is complete the data quality control process is still necessary to identify when rodents, weather, roadside maintenance or other activities negatively impact the sensor performance.

1.3.5.2.1. Data Quality Control Acceptance Process

As previously discussed the sensors must provide data that meets the minimum level of data quality as required in the contract documents. Contract payment should be weighted to rely heavily on sensor data quality, as leverage to correct deficiencies is lost when a large percentage of contract payments have been made prior to determining if the data meets minimum quality levels.

1.3.5.2.2. Sensor Health Monitoring to Schedule Maintenance Activities

Ongoing health monitoring is critical to system wide data quality confidence and performance. The need to test sensor data quality prior to acceptance during different weather conditions can detect splice failures and other sensor anomalies that can degrade sensor data quality. As well, electronic equipment is susceptible to damage from weather related events, such as electrical storms and lightning damage. Ongoing health monitoring of sensor data can quickly detect such damage and focus maintenance efforts where they will produce the greatest system-wide benefit.

The DMAIC model is an important tool for freeway sensor data quality and has been successfully applied to address the data quality issue within the context of traffic network data (6); specifically the accuracy of Weight in Motion data used by the Indiana State Police for commercial vehicle enforcement. The process has also been addressed preliminarily within the context of ITS sensors by the project “Performance Metrics for Freeway Sensors” (5). This project has further applied the DMAIC model to provide a procedure for achieving and maintaining quality sensor data.

This procedure was developed by implementing the steps 2 through 5 of the DMAIC model (Figure 1.2). The data collection and analysis was conducted by co-locating sensors at a test location and analyzing the data to determine questionable data occurrences. The Average Effective Vehicle Length test was found to be an important tool for determining potential error occurrence; however it is somewhat limited due to factors such as traffic composition, and occupancy reporting precision. Heuristic knowledge of site characteristics however can improve the AEVL test's effectiveness by narrowing the test upper and lower limits by using archived sensor data from the same location.

CHAPTER 2. LITERATURE REVIEW

2.1. Recent Work

The rapid expansion of ITS use within the U.S., as a means to preserve existing freeway capacity has led to the increased instrumentation of freeways and the reliance on freeway sensors to assist operators in Freeway Traffic Management (7). The quality of data has also received considerable scrutiny from the ITS community, and has been the subject of some recent research (8). There has also been an effort to reach a consensus as the minimum data quality level, as shown in Table 2.1.

Table 2.1 Guidelines for Traffic Sensor Data Quality Levels (9)

Measure	**Data Quality Levels**	**Requirement**
Accuracy	Good	10-15% error
	Better	5-10% error
	Best	< 5% error

New freeway sensor technology has been the subject of extensive research efforts in the past several years in part due to the desire to replace the Inductive Loop Detector (ILD). Inductive Loops, while a mature technology that can provide excellent data, are being replaced in the U.S. due to the associated high cost of installation and maintenance (10). The search for replacement technology has led to the evaluation of several separate types of vehicle detection technology for use in the freeway detection to replace the use of ILD's (11,12,13). The majority of the research has been focused on sensor evaluation and side by side comparisons of different sensor technologies. The typical evaluation compares the volume, speed and occupancy values reported by sensors co-located at the same site (10,11,12,13).

Additional research has also been conducted in the area of ITS Data Quality by the University of Virginia and the Virginia Transportation Research Council (VTRC). In 2003 a Final Report was published by the VTRC in which a procedure was developed to assess ITS sensor data quality (14). Suggested methods of validating data quality involved four methods: manual, video analysis, temporary intrusive detector installation and temporary non-intrusive detector installation. Manual methods involved human benchmarking volume and speed through interval volume counting and speed validation with either radar or laser speed measuring instruments. Video analysis methods were based on using either existing traffic monitoring cameras or a mobile video collection van and post processing the data for interval volume and speed through time-based video editing and determining the time between two know points on the roadway. Temporary intrusive detectors would be mounted in the traffic lanes. Examples of intrusive detectors would be temporary inductive loops and pneumatic tube. Non-intrusive temporary detectors are based on using a technology such as sidefire radar, acoustic detectors or video image vehicle detection systems.

The analysis of data quality suggested the availability of two approaches: rigorous statistical hypothesis testing and qualitative testing using plots and less rigorous statistics. Hypothesis testing would be aimed at determining if the means of the two samples (benchmark and field) are statistically equivalent, and thus representing "good" data quality. Rigorous statistical hypothesis testing was rejected as the preferred method in favor of the qualitative approach, due to the likelihood that the sensitivity of rigorous hypothesis testing would lead to indications that the data is not of sufficient quality, when from a practical perspective, the data are of acceptable quality. The requisite knowledge of statistics to properly interpret such tests is often not consistent with the skills of field personnel. Therefore the qualitative testing and less rigorous numerical methods were chosen to assess the quality of sensor data. Two types of plots for data quality assessment were selected: time series plots, and scatter plots. The time series plotting was used to evaluate the field sensor data and the benchmark data against each on the y-axis vs. time on the x-axis. A qualitative approach is used to determine data quality. Scatter plots are used to plot the field data on one axis and the benchmark data on the other axis. Data quality is assessed by computing the Pearson correlation coefficient.

The research project was important in that it also suggested that the sensor data be analyzed on a lane by lane basis as opposed to a site basis to determine data quality. However the research did not include the assessment of sensor occupancy, as volume and speed were the principle measures that were researched. Therefore any sort of performance metric based on traffic flow principles such as Average Effective Vehicle Length (15) is not possible.

2.2. Discussion

There have been many research projects aimed at determining the relative performance of freeway sensors with respect to existing ILD technology (10,11,12,13). The typical evaluation compares the volume, speed and occupancy values reported by sensors co-located at the same site. However applicable research in the area of sensor data quality and ongoing monitoring has been undertaken with respect to Weight-In-Motion (6) and Traffic Sensor Data Screening at an aggregate level (15, 16). The weigh in motion research has applied the DMAIC model to the area of data quality and uses statistical quality control for sensor health monitoring. The Traffic Sensor Data Screening aggregate data measures involve a metric known as Average Effective Vehicle Length (AEVL), which uses an approximate function of volume, speed and occupancy reported by sensors to estimate an average effective vehicle length (15). The AEVL test, as well as other tests, known as threshold value tests have been used as data screening tools for an evaluation of the DynaMIT program, which is a traffic estimation and prediction system (17). The AEVL will be utilized within the scope of this project to provide an initial tool for screening sensor health.

CHAPTER 3. ITS SENSOR PERFORMANCE METRICS

The second step of the DMAIC process involves identifying performance measurements (metrics) used for decision making and collecting and processing data. The second step is shown in Figure 3.1, which is further elaborated in this chapter and also in Chapter 5 identifies the elements necessary to perform the analysis step.

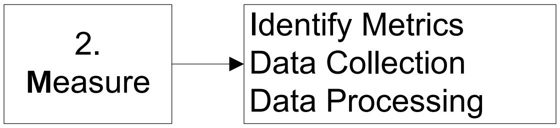


Figure 3.1 DMAIC Process – Measure Step

The continuous monitoring of ITS sensors for data quality can be accomplished through the implementation of several performance metrics. These metrics are derived from the sensor data and can be used to assess the data quality. A very good method for evaluating sensor health is by co-locating the sensors, thereby obtaining two independent sources of data to compare. The sensor test site, located on I-65 at the milemarker 128 (mm128), used for this evaluation consisted of three different sensors: 3M Microloops, and two side-fire radar units. The site was well suited for the purpose of comparing sensor data due to the fact that vehicular flow was the same between sensors. Temporal and spatial offsets were also small due to the relative proximity of the sensors. This section describes the following metrics for evaluating sensor health:

- Volume Comparison
- Speed Comparison
- Occupancy Comparison
- Average Effective Vehicle Length

3.1. Volume Comparison

The performance metric relating to volume compares the cumulative volume of co-located sensors. The procedure for computing this metric is as follows:

- Using interval volumes compute a running cumulative volume for each lane. This is accomplished by selecting the first record common to both sets of data and adding the next interval volume.
- Prepare a plot of the Cumulative Volume vs. Time using all relevant data on the same plot. An example plot is shown in Figure 3.2

The use of this metric is evident when visually comparing the difference between sensor cumulative volumes. Divergence of cumulative volume traces indicate the need for further investigation of that ITS sensor site.

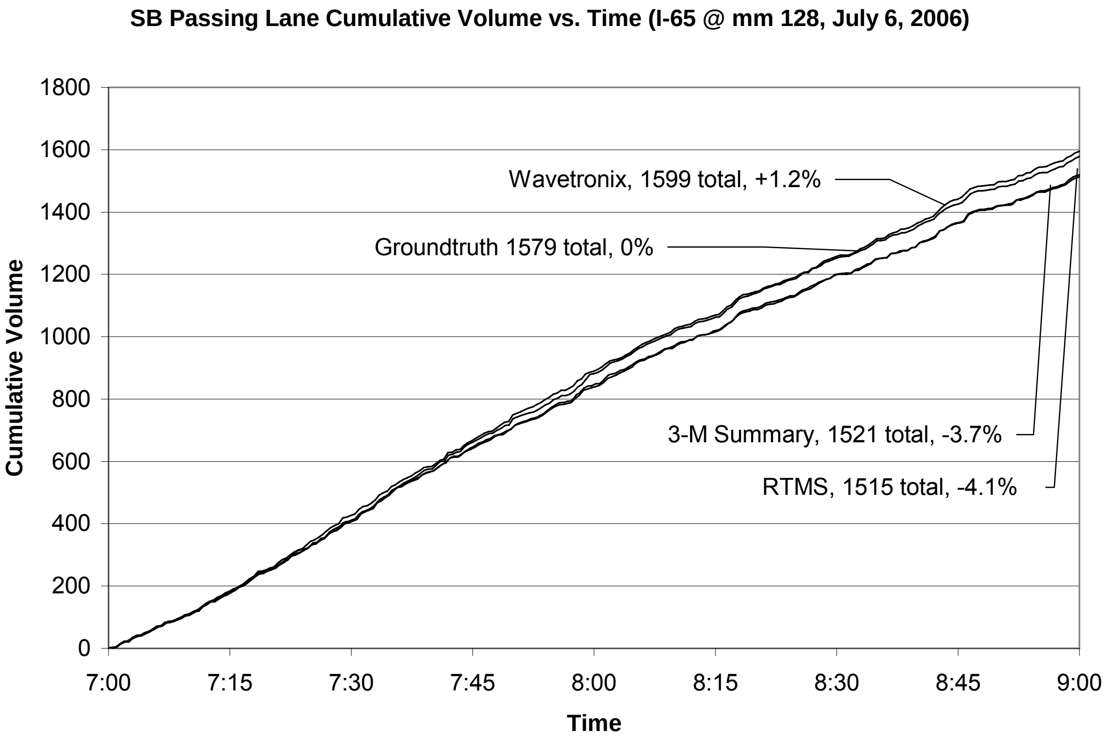
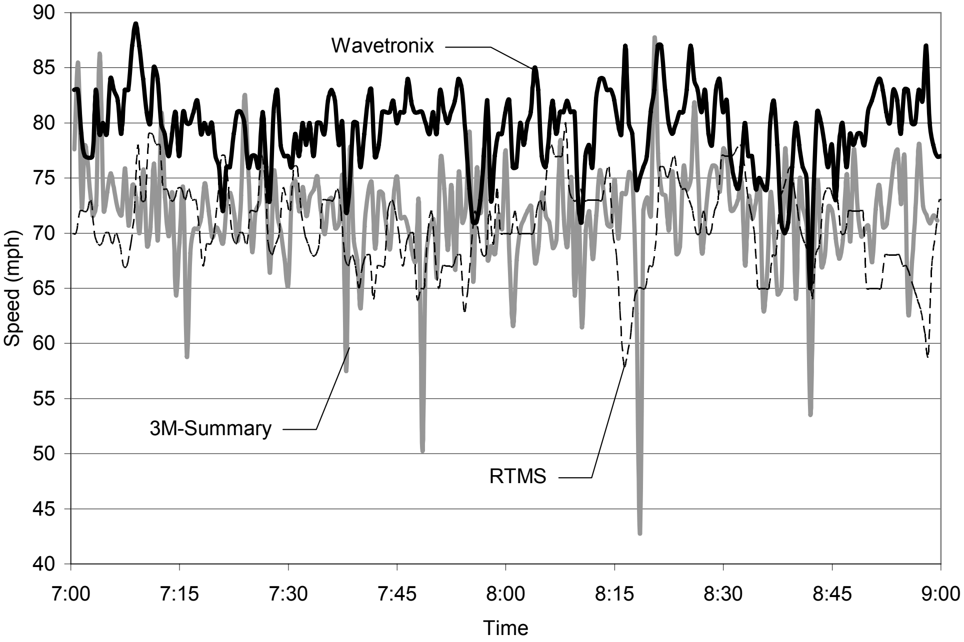


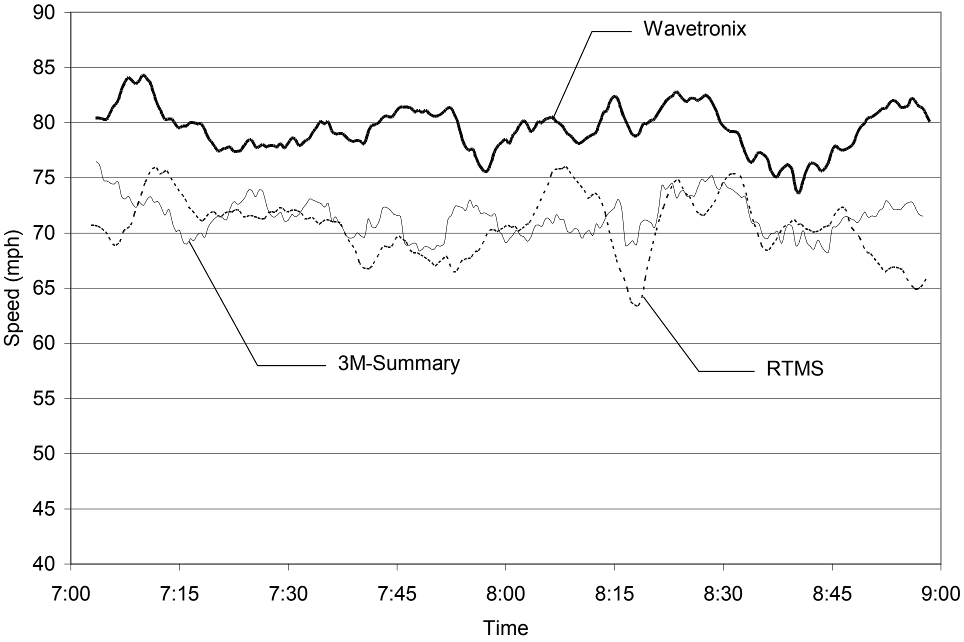
Figure 3.2 Example of Cumulative Volume vs. Time Plot

3.2. Speed Comparison

The comparison of sensor speeds with respect to time is another performance metric which can be used to assess the quality of the data being provided by ITS sensors. The interval speeds are plotted vs. time and visually compared to each other. Significant variations in speed over time are indicative of a problem worthy of further investigation. Data aggregation can be used to remove "sensor noise" from the plots. For example a 5 minute moving average speed plot vs. time is easier to visually inspect than a 30 second interval speed vs. time plot. Such an example difference is shown in Figure 3.3.



a) 30 second interval speed vs. time



b) 5 Min. moving average speed vs. time plot

Figure 3.3 Example of Average Speed vs. Time Plots

3.3. Occupancy Comparison

Sensor Occupancy is amount of time during the interval that a vehicle is reported in the detection zone. Sensor occupancy can be calculated using the following formula:

$$\text{Decimal Occupancy} = \frac{\sum \text{Detection Duration}}{\text{Interval Duration}} \qquad \text{Equation 3.1}$$

Occupancy can either be reported as a decimal or percentage. The sensor on-time can then be reverse calculated by multiplying the occupancy by the interval length, as shown using the following formula:

$$\text{Sensor On Time} = \text{Decimal Occupancy} * \text{Interval Duration} \qquad \text{Equation 3.2}$$

Evaluation of the occupancy metric is accomplished by visually comparing the traces of the various sensors with respect to each other. Significant divergence of the traces is indicative of a potential sensor data issue. An example of the cumulative 'on-time' vs. time plot is shown in Figure 3.4

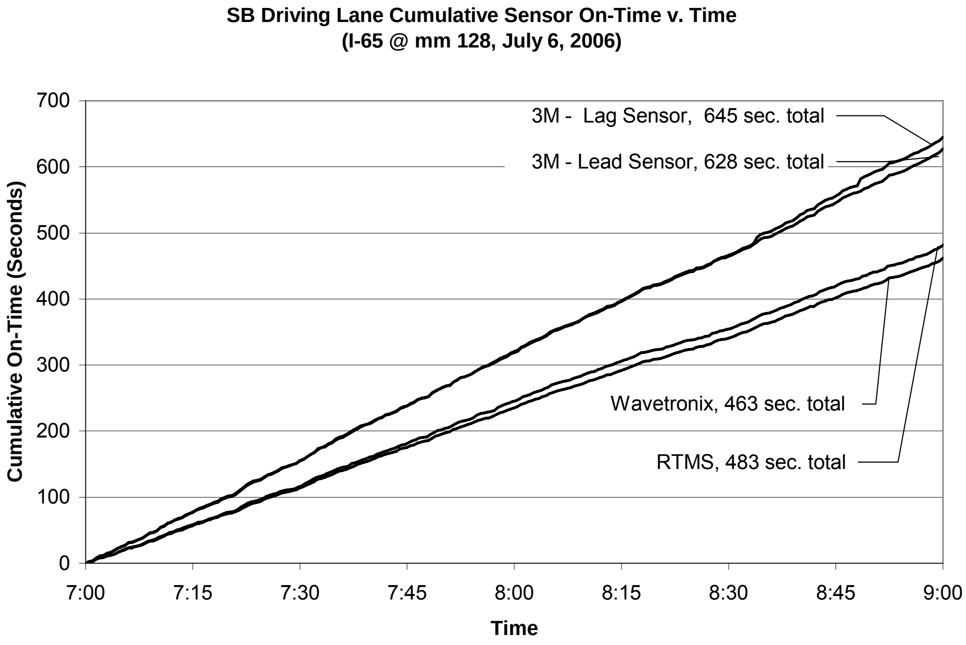


Figure 3.4 Example of Cumulative Sensor 'On-Time' vs. Time

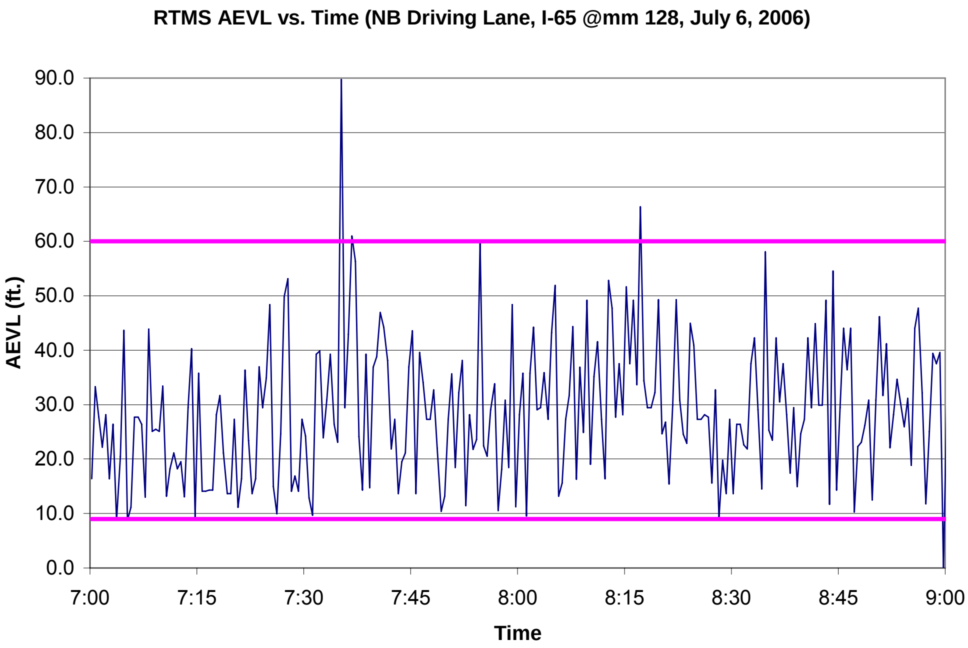
3.4. Average Effective Vehicle Length

The Average Effective Vehicle Length (AEVL) is an approximate function of the volume, speed and occupancy. The AEVL can be calculated per interval using the following formula:

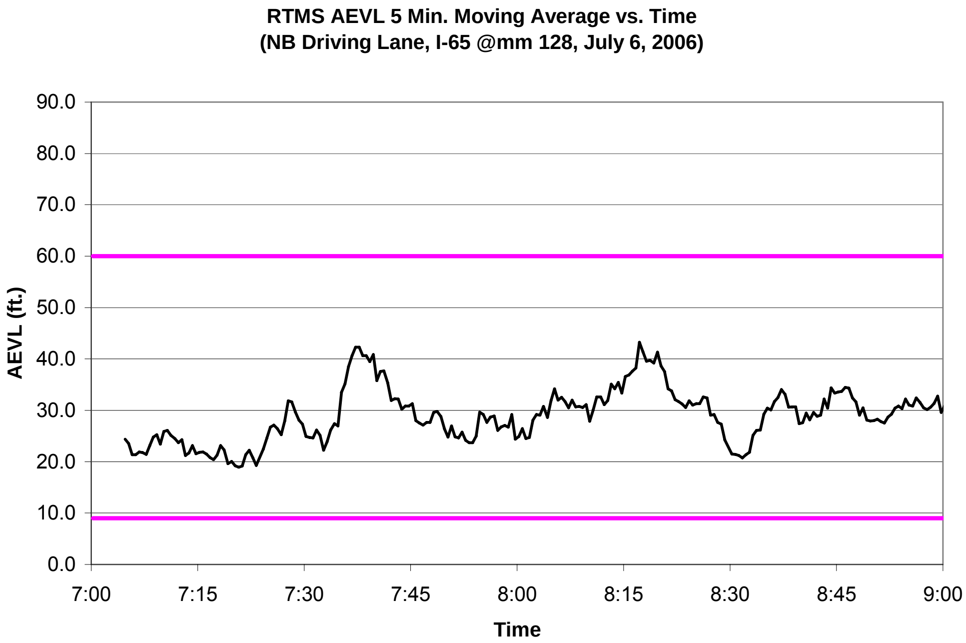
$$\mathrm{AEVL} = \frac{(5280 * \mathrm{V} * \mathrm{O})}{\mathrm{q}} \qquad \text{Equation 3.3}$$

Where:
V = interval average speed (miles/hour),
O = interval decimal occupancy (Equation 3.1), and
q = interval hourly flow rate (vehicles/hour)

The interval AEVL values can than be plotted and compared to previously set upper and lower limits (8), as shown in Figure 3.5. The use of AEVL as a performance metric is subject to several limitations (5), such as vehicle lengths and speeds being fairly uniform and occupancy values being lower than 20%. The advantage to this metric lies in the ability to use the AEVL for screening ITS sensor sites based on a predetermined percentage of AEVL test results falling outside the acceptable limits, without the need for plotting and analyzing graphs.



a) 30 second interval AEVL vs. Time



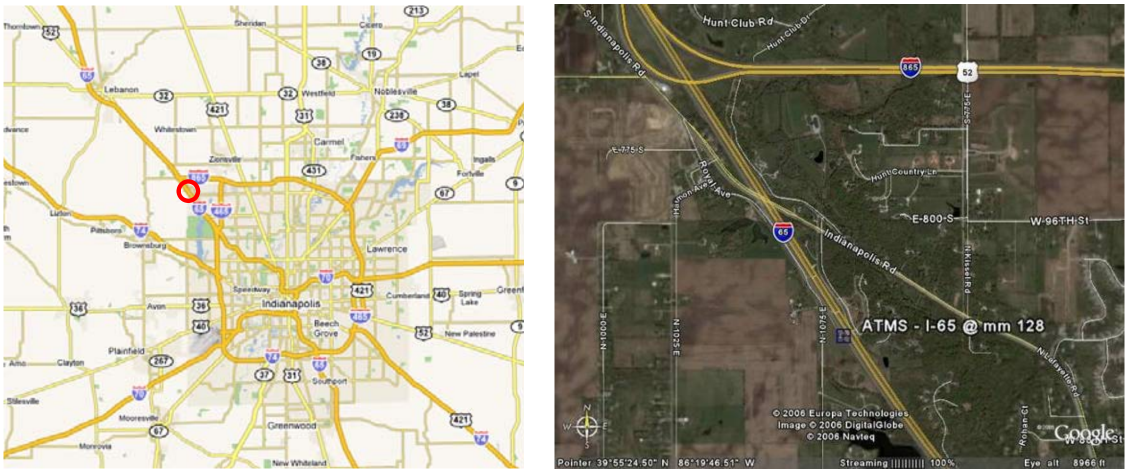
b) 5 Min. Moving Average AEVL vs. Time

Figure 3.5 Example of AEVL Test Plots

CHAPTER 4. EVALUATION SITE

4.1. Description of I-65 ATMS Site

The sensor quality control test bed is located near the milemarker 128 on the west side of I-65, in Hendricks County, Indiana, as shown in Figure 4.1. The site is also used as an ITS freeway sensor site. The equipment located at this site consisted of a communications shed, communications tower, emergency power generator, and fence enclosure.

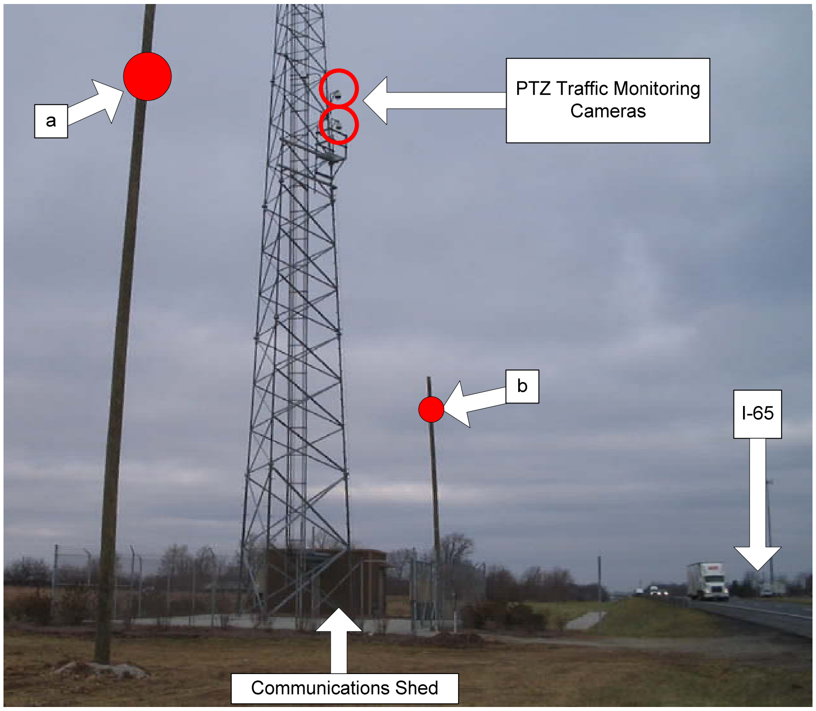


a) I-65 @ mm128 Site Location

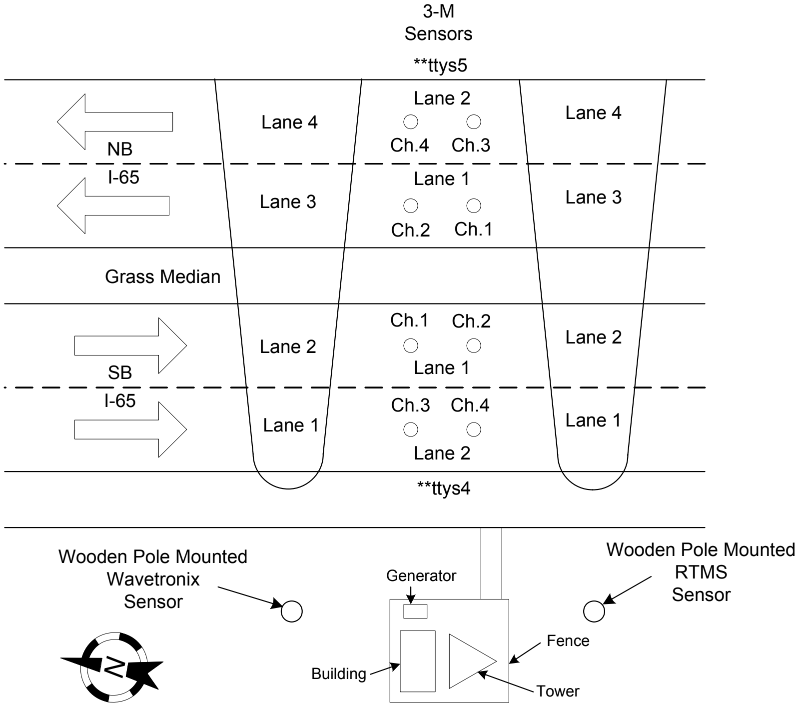
b) Site Location

Figure 4.1 I-65 ITS Sensor Quality Control Test Location

The site is also equipped with two Pan, Tilt and Zoom (PTZ) capable cameras for traffic monitoring. An outside image of the mm 128 site is shown in Figure 4.2. The communications shed and generator are shown in Figure 4.3.



a)Outside Image of MM 128 site



b) Layout of mm 128 ITS Sensor Site

Figure 4.2 Milemarker 128 site on I-65, Hendricks Co., IN

Figure 4.3 ATMS Communications Shed @ mm 128 on I-65

The existence of video capability at the mm 128 site provided the ability to groundtruth sensor data. The groundtruthing analysis was facilitated by overlaying the existing video from one of the mm 128 PTZ cameras with a time/date stamp and dynamic detector states. An example of the dynamic overlay is shown in Figure 4.4. This was done using an Autoscope 2020 (Figure 4.5). The label detectors are set to change color when the Canoga detector card senses a vehicle. An example of the video screen including the Autoscope overlay is shown in Figure 4.4.

Figure 4.4 View from PTZ Camera showing Autoscope 2020 Overlay and Dynamic Label Detectors

There is one label detector corresponding to each Microloop sensor. The image in Figure 4.4 shows that there was detection by the Microloops in the SB Passing Lane at 08:33:50 on July 6, 2006. The Autoscope input channels, 3M Microloop channels and label detectors are identified with respect to each other in Table 4.1. Use of the Autoscope 2020 system time overlay also made the synchronization between the time stamps of the Microloop vehicle detection occurrences and the video time much easier.

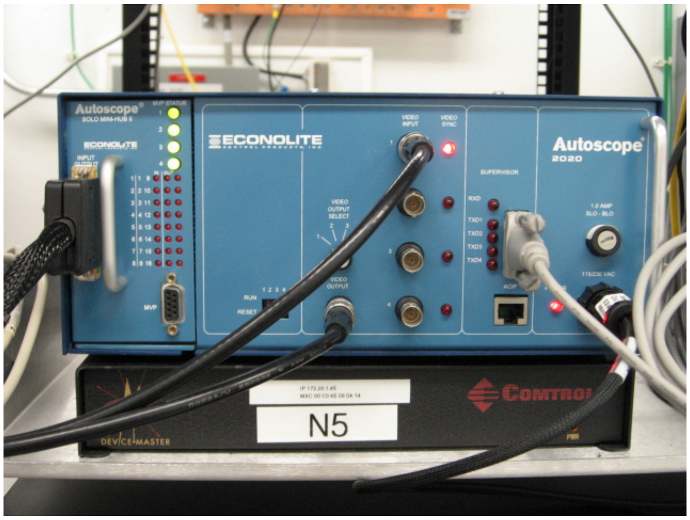


Figure 4.5 Autoscope 2020 Device in I-65 mm128 communications hut

Table 4.1 Microloop Channels/Cards -Autoscope Channel and Dynamic Labels

3M Microloop Channel		Autoscope 2020	
Northbound	Southbound	Channel Number	Label Detector Name
	1	1	SB Passing Lead
	2	2	SB Passing Lag
	3	3	SB Driving Lead
	4	4	SB Driving Lag
1		5	NB Passing Lead
2		6	NB Passing Lag
3		7	NB Driving Lead
4		8	NB Driving Lag

4.2. Data Collection Methodology

Data from the mm 128 test location was collected using an Aries Field Processor (AFP), from Iron Mountain Systems, Inc. The AFP used for this data collection is located within the communications shed at the mm128 and is shown in Figure 4.6.

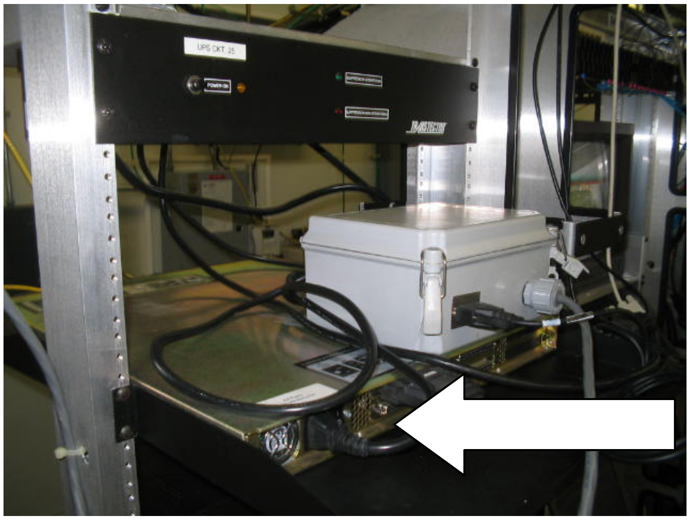


Figure 4.6 Aries Field Processor @ mm 128 ITS Site

The AFP is a Linux based machine which collected and binned sensor data using an Iron Mountain Systems, Inc. program. Data recorded by the AFP consisted of summary files for each of the sensors, as well as unprocessed data from the 3M Canoga detector cards. The overall data collection architecture, including applicable Internet Protocol (IP) addresses is shown in Figure 4.7.

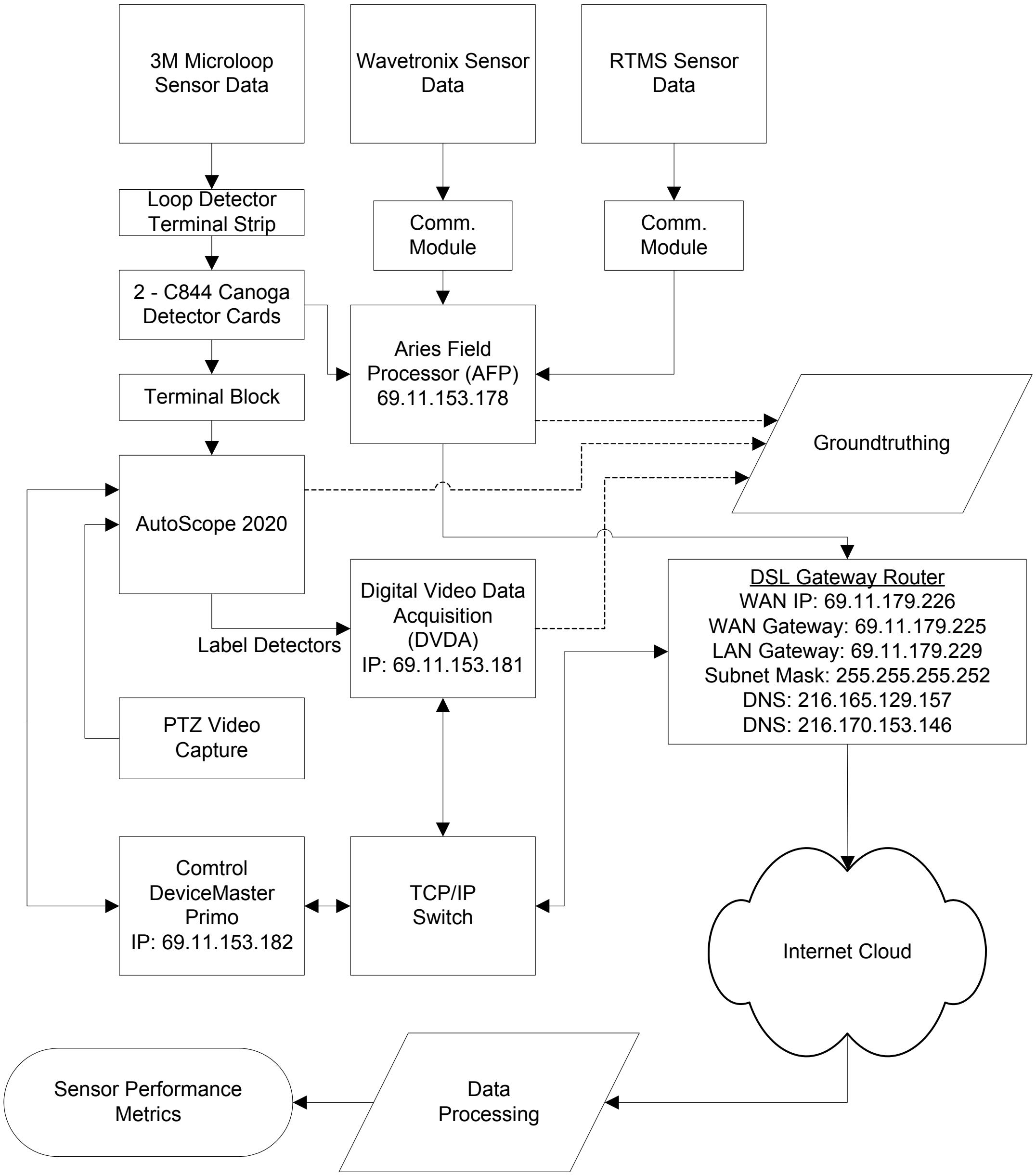


Figure 4.7 Data Collection Architecture

4.2.1. Side-Fire Radar Data Routing

Sidefire radar data routing is similar for both sensor and consists of the following path:

- Pole Mounted Sidefire Radar Unit (RTMS (point a in Figure 4.2, or Wavetronix Smartsensor (point b in Figure 4.2))
- Proprietary Sensor Communication Module (Figure 4.8 &Figure 4.9)
- AFP (Figure 4.6)
- Internet Switch (Figure 4.10)
- PC for Data Processing/Analysis

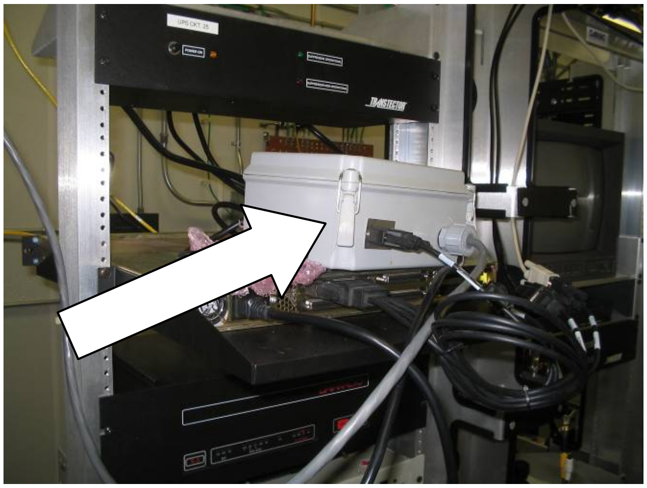


Figure 4.8 Proprietary RTMS Communication Module

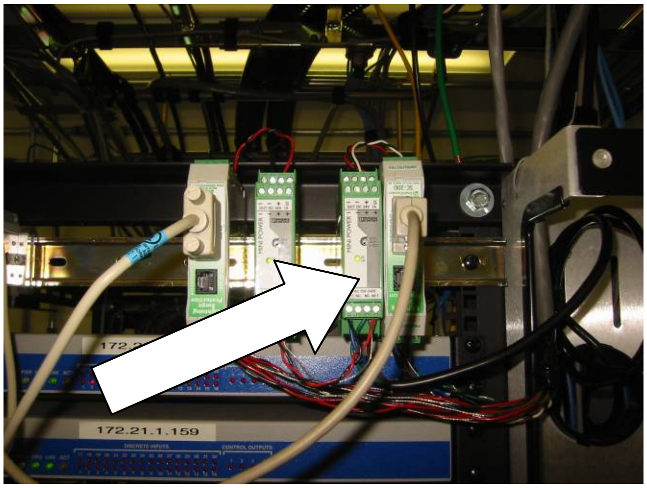


Figure 4.9 Proprietary Wavetronix SmartSensor Communication Module

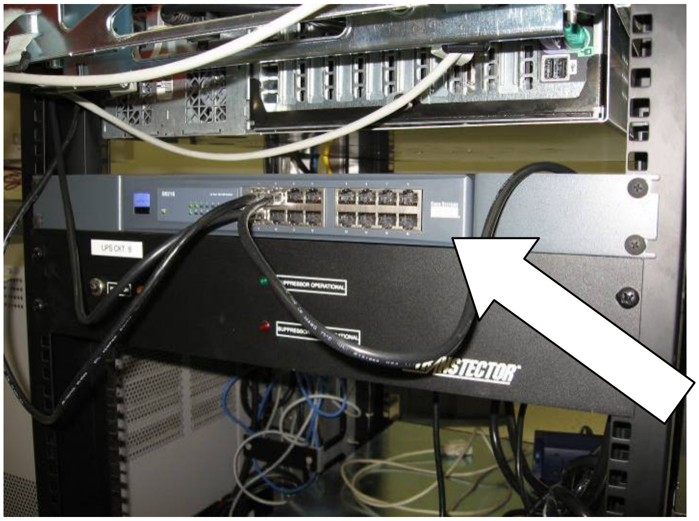


Figure 4.10 Internet Switch @ mm 128 site

4.2.2. Microloop Sensor Data Routing

The data routing for the Microloop sensors is more involved. The cabling from the sensors is initially connected to a Loop Detector Terminal Strip (Figure 4.11). The Microloop contact closures for the sensors have been attached to inputs for the Autoscope 2020 device (Figure 4.5) at the terminal block shown in Figure 4.12 to provide the dynamic labeling on the video overlay (Figure 4.4). The raw and summary information, from the Canoga Detector Cards (Figure 4.13), is then routed to the AFP for storage.

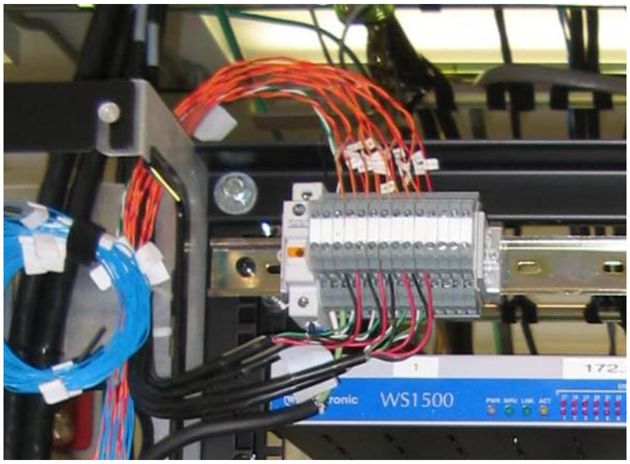


Figure 4.11 3M Microloop Loop Detector Terminal Strip

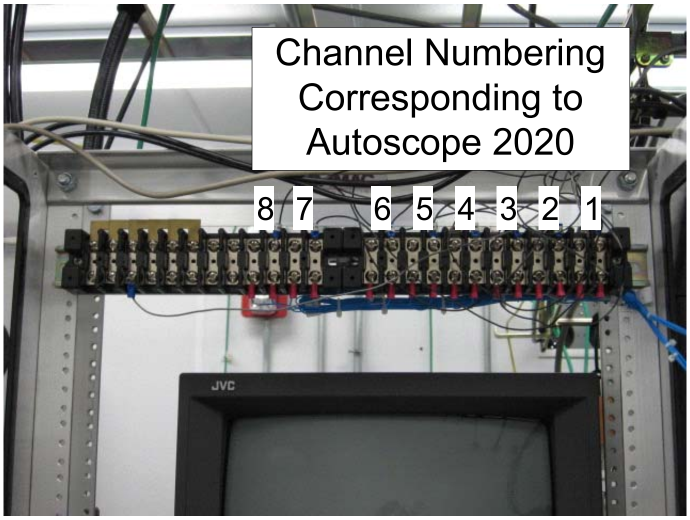


Figure 4.12 3M Microloop/Autoscope 2020 Terminal Block for Contact Closure Connection

Figure 4.13 Canoga Detector Cards at mm128 Site

4.3. Site Sensors

The mm 128 site (Figure 4.2) is equipped with three independent sensor technologies. The site was initially instrumented with Microloop sensors as part of the INDOT Advanced Traffic Management System, and the site was considered ideal to co-locate additional sensors for the station health monitoring project due to the existing tower mounted traffic monitoring cameras that could be used for groundtruthing the sensor data.

4.4. Lane Naming Convention

Due to sensor designs, the lane naming convention for the sidefire radar sensors differs from the lane naming convention of the Microloop sensors. Figure 4.2 summarizes the naming convention. The following sub-sections explain the conventions.

4.4.1. Microloop Lane Naming/Numbering Convention

The lane naming convention used by Microloop sensors is based on assigning the lane closest to the median as lane 1 and additional lanes to the right are in ascending order. This is shown in Figure 4.2, as the SB Passing Lane is Lane 1 and the SB Driving Lane is Lane 2, according to the Microloop convention. The direction of travel is an additional parameter to the lane numbering convention, and must be specified separately. For example, the SB Driving Lane would be called SB Microloop Lane 2.

4.4.2. Sidefire Radar Lane Naming/Numbering Convention

The lane naming convention for the sidefire radar systems in this project is based on assigning the closest lane as lane 1 and increasing the lane number as the distance increases from the sensor. Thus the SB Driving Lane is Lane 1 for the sidefire radar sensors, Lane 2 is the SB Passing Lane, Lane 3 is the NB Passing Lane, and Lane 4 is the NB Driving Lane. The sidefire radars at the mm128 site are capable of detecting up to eight lanes of traffic. Even though there are only four traffic lanes at the mm 128 site the sidefire radar units still report default values for eight lanes.

4.5. 3M Microloop Sensors

The mm128 Microloop sensors are Model 702 single probes, arranged in a “lead-lag” configuration. The typical Microloop “lead-lag” deployment is shown in Figure 4.14.

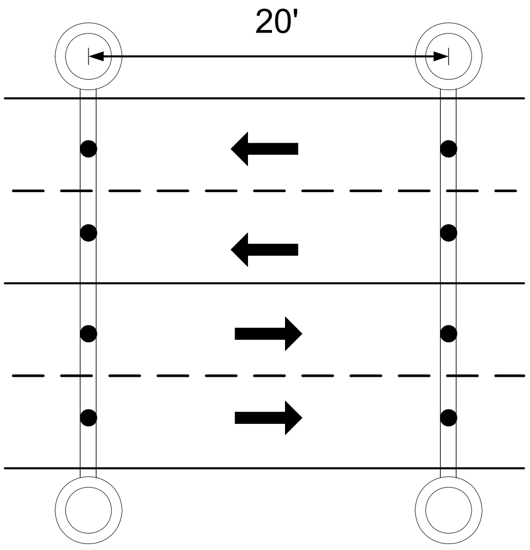


Figure 4.14 3M Microloop Typical Sensor Layout

The two Canoga C824T-F Detector Cards each have 4 channels, thus each Canoga Detector Card is capable of handling the inputs from two lanes in the “lead-lag” deployment.

The Microloop probes are spliced within the handhole and a ‘homerun’ cable is then connected to the communications shed from each handhole. Due to the potential presence of water in the handholes, a waterproof splicing system is used to ensure proper connection integrity (Figure 4.15).

a) Microloop Handhole w/splices

b) 3M Scotchcast™ 3832 Buried Service Wire Encapsulation Kit (18)

Figure 4.15 Microloop Sensor Splicing

4.5.1.1. Microloop Sensor Calibration

The Microloop sensors at the mm 128 site were calibrated by Carrier & Gable and a representative of 3M on January 26 & 27, 2006 (19), using a laser instrument to calibrate vehicle speeds. The findings are summarized in Table 4.2.

Table 4.2 Calibrated Microloop Lead-Lag Separation Values for I-65 @ mm 128

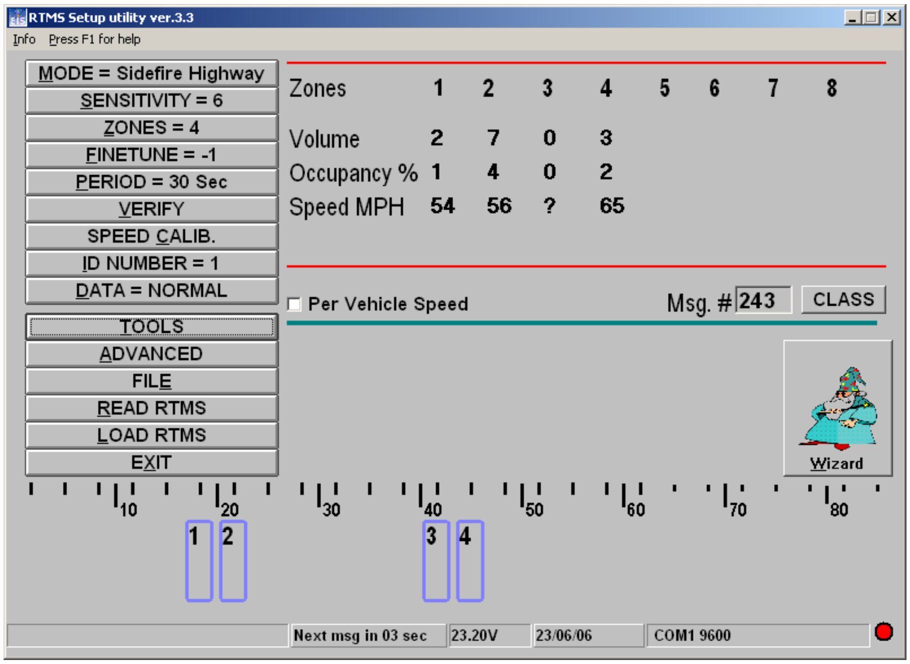
Lane	Microloop Channels	Lead-Lag Distance
SB Passing	1 & 2	16.5 ft.
SB Driving	3 & 4	16.7 ft
NB Passing	1 & 2	19.8 ft.
NB Driving	3 & 4	20.0 ft.

4.6. RTMS Sensor Installation

The RTMS sensor is installed approximately 70 feet south of the Microloop sensor speedtrap, as shown in Figure 4.2 (a, point A) and (b). The sensor is mounted to a standard wooden utility pole, with vendor supplied hardware, approximately 17 feet above the roadway.

4.6.1.1. RTMS Sensor Calibration

The RTMS sensor calibration was performed by EIS personnel on December 13, 2005, using WinRTMS software. The process consisted of identifying the number of 'detection zones' or lanes and aligning the corresponding zone with identified 'screen blips' on the graphical user interface. The actual zones at the I-65 @ mm128 ITS test site are shown on the screen capture in Figure 4.16.



MODE = Sidefire Highway
SENSITIVITY = 6
ZONES = 4
FINETUNE = -1
PERIOD = 30 Sec
ID NUMBER = 1
DATA = NORMAL

Zones	1	2	3	4	5	6	7	8
Volume	2	7	0	3				
Occupancy %	1	4	0	2				
Speed MPH	54	56	?	65				

☐ Per Vehicle Speed
Msg. # 243

Next msg in 03 sec | 23.20V | 23/06/06 | COM1 9600

Figure 4.16 Screen Capture of WinRTMS setup screen for I-65 @ mm128 ITS

Speed calibration for the RTMS was accomplished by comparing the reported average interval speeds as shown in Figure 4.16 with a ‘reasonable value’ associated with the roadway section and adjusting the speed coefficients for each detection zone. Quite surprisingly no laser or radar instruments were used to validate the RTMS speed data.

4.7. Wavetronix Sensor Installation

The Wavetronix Smartsensor 105 is installed approximately 30 feet north of the Microloop sensor speedtrap, as point b in Figure 4.2 (a) and in Figure 4.2 (b). The sensor is mounted to a standard wooden utility pole, with vendor supplied hardware, approximately 17 feet above the adjacent ground elevation. The Wavetronix Smartsensor 105 is shown in Figure 4.17.

Figure 4.17 Wavetronix Smartsensor 105 at I-65 @ mm 128 ITS Site

4.7.1.1. Wavetronix Smartsensor Calibration

The Smartsensor 105 is calibrated using proprietary Wavetronix software called SmartSensor Manager Ver. 2.2. There is an automatic lane configuration process within the software that starts detecting vehicles and graphically shows the lanes on the Graphical User Interface (GUI). A representation of the vehicles within the lanes is also shown on the interface. An example of the interface is shown in Figure 4.18. Similar to the RTMS unit the Smartsensor speed calibration was performed without the use of Laser or Radar instruments.

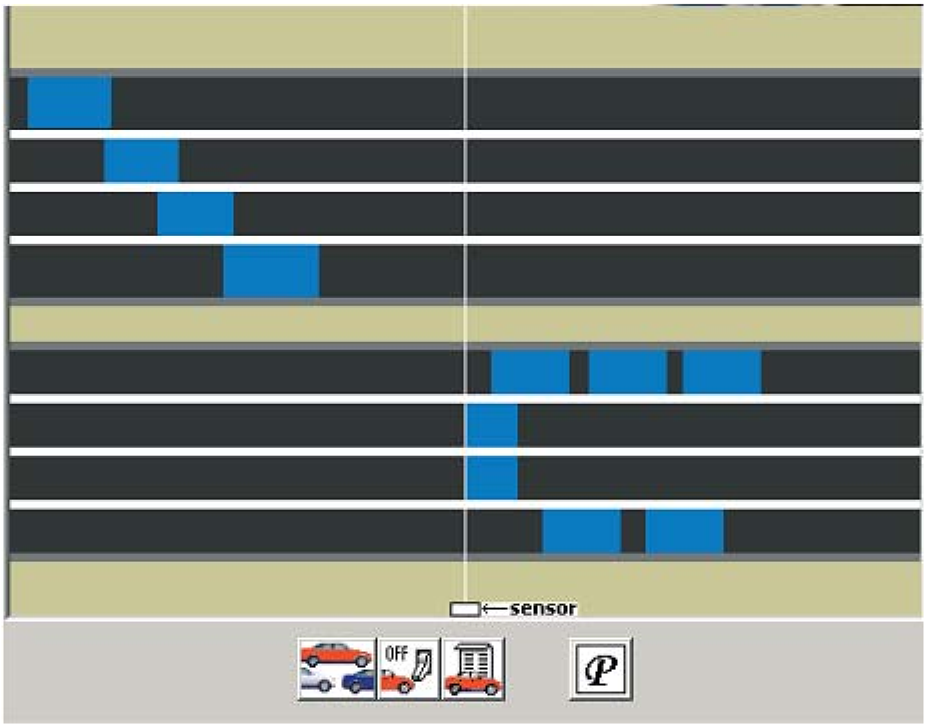


Figure 4.18 Example of Wavetronix SmartSensor Manager Lane Configuration GUI, showing four lanes in each direction of travel

CHAPTER 5. PRELIMINARY DATA COLLECTION

The use of the performance metrics discussed in the previous sections enabled the research team to troubleshoot the test bed for sensor errors within the timeframe of the project. A timeline of events within the project, shown in Table 5.1, indicates how the metrics were used during the project to calibrate and analyze the sensor data. Several times the results of initial analyses resulted in corrective action, which reflects an application of the discussed performance metrics to a real world scenario.

5.1.1. Test Bed Concept

In the Fall of 2005 the concept for use of the mm 128 site was finalized. A meeting was held at the mm 128 site, with INDOT personnel, Purdue researchers and technical representatives from the sidefire radar vendors. The objective was to determine the proper placement of the sidefire radar units in order to avoid interference between the units. It was also determined that the sidefire units would be calibrated by the supplier representatives in order to evaluate the ease of calibration.

Table 5.1 Table of Milestones and Summary of Events

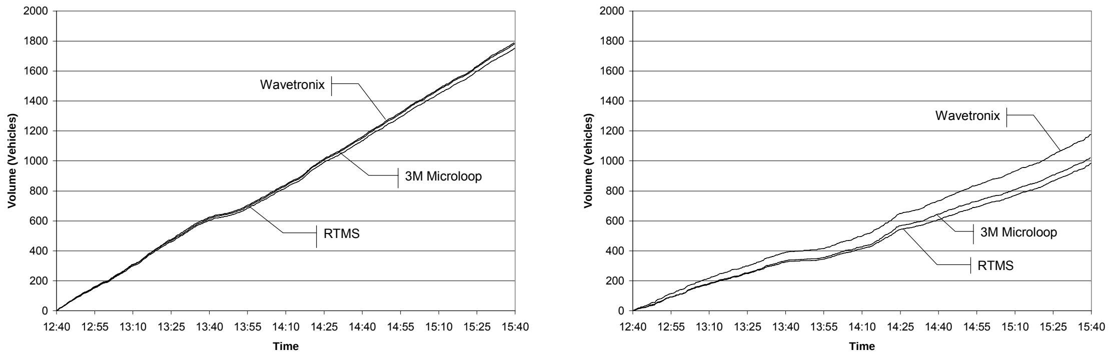
Date	Milestone	Findings	Reference Section
Late 2005	Test Bed Concept		5.1.1
2/2006	Functional Specification Satisfied	OK to proceed with Data Collection	5.1.2
2/14/2006	Initial Video Collection – DVD Camcorder	Needed Dynamic Labeling for Microloop contact closures	5.1.3
March 2006	DL3MRAW program debugged		5.1.4
5/12/2006	Data Collection	RTMS problem	5.1.5
5/17/2006	RTMS Replaced	Occupancy discrepancy between side-fire units	5.1.6
5/26/2006	Investigated occupancy reporting discrepancy	RTMS unit corrupted due to incompatible firmware issue	5.1.7
6/11/2006	Wavetronix Occupancy Scaled	Occupancy scaling resulted in better agreement	5.1.8
7/5/2006	RTMS Replaced		5.1.9
8/6/2006	Congested Period Evaluated	Full Metric Implementation	5.1.10

5.1.2. Functional Specification Satisfied

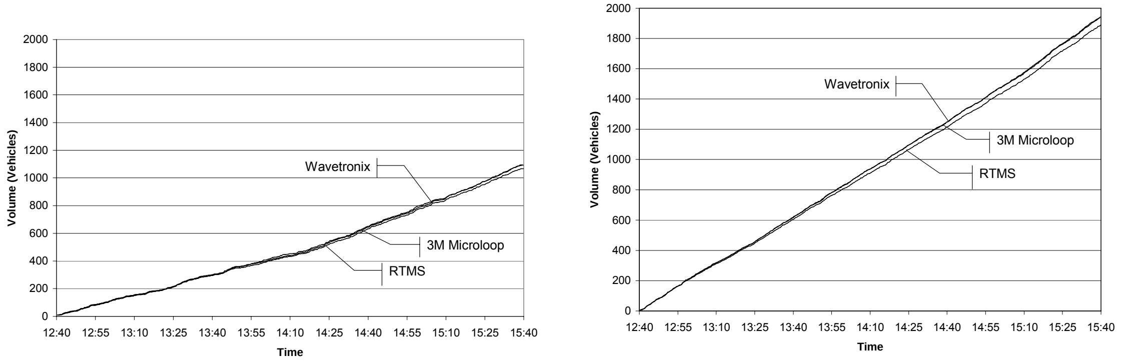
The process of formatting the data collection for analysis was iterative between the software vendor (Iron Mountain Systems, Inc.) and the research team. The process involved determining the file naming conventions, and the formatting of the data for both the summary files and the raw Microloop data. The largest challenges arose from the raw Microloop data ensuring that the data provided in the files was sufficient for use in evaluating the performance metrics. The functional specification was satisfied in February of 2006.

5.1.3. Initial Video Collection

Initial Video collection occurred on February 14, 2006 for three hours. The subsequent analysis of the data showed the need for an overlay on the video in order to determine the time offset between the AFP time and video time. It was also determined that the dynamic labels from the Autoscope 2020 would assist in determining the time offset interval. Initially the analysis from early data collections involved analysis of the summary data files and cumulative volume comparison. The results of this data collection are show in Figure 5.1. A qualitative interpretation of the results indicates that the least agreement between sensors occurs in SB Passing lane (Figure 5.1, b), however no groundtruthing was performed to determine the actual volume. All other lanes indicated excellent cumulative volume vs. time agreement Figure 5.1, a,c,d).



a) SB Driving Lane b) SB Passing Lane



c) NB Passing Lane d) NB Driving Lane

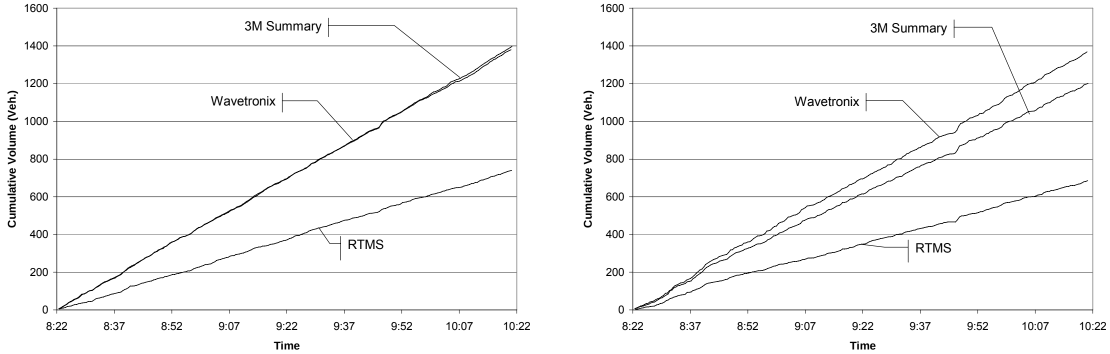
Figure 5.1 February 14, 2006 Cumulative Volume vs. time plots from I-65 @ mm 128 site

5.1.4. DL3MRAW program debugged

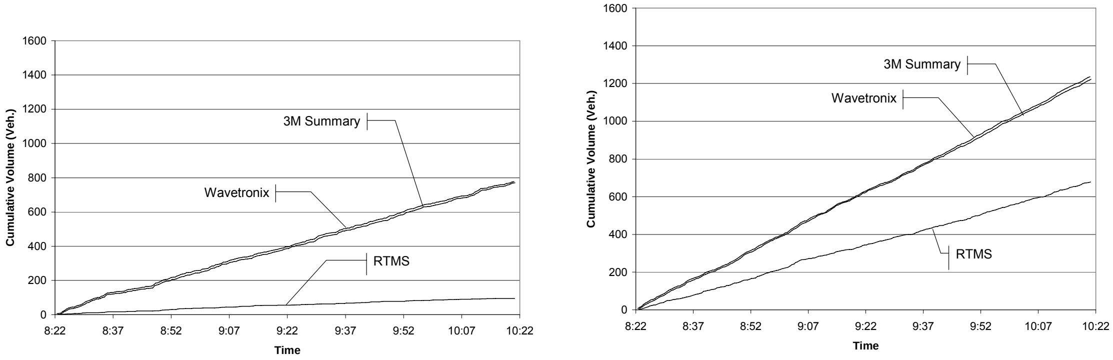
The program required to convert the raw data file from binary format to a comma delimited file was initially reading the entire raw file into memory prior to outputting the decimal format data. This became a problem trying to convert data files that contained more than a couple of hour's worth of data. The problem was rectified by Iron Mountain Systems, Inc. by revising the program to input and output the data line by line.

5.1.5. RTMS Unit Data Suspect

Data was collected on May 12, 2006 for two hours and analyzed using the cumulative volume metric. The resulting cumulative volume vs. time plots are shown in Figure 5.2, and clearly indicate that the RTMS unit data is suspect, as all lanes are indicating serious underreporting of volume. This analysis prompted contact with EIS for assistance in troubleshooting the unit and its ultimate replacement on the May 17, 2006.



a) SB Driving Lane b) SB Passing Lane



c) NB Passing Lane d) NB Driving Lane

Figure 5.2 May 12, 2006 Cumulative Volume vs. time plots from I-65 @ mm 128 site

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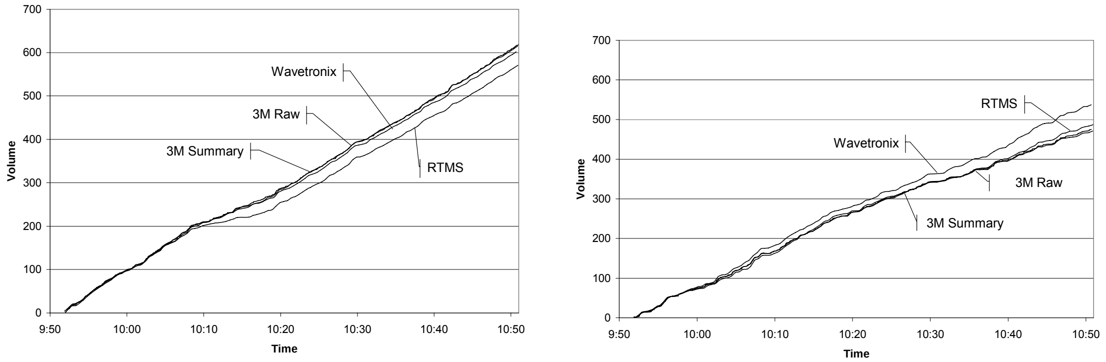
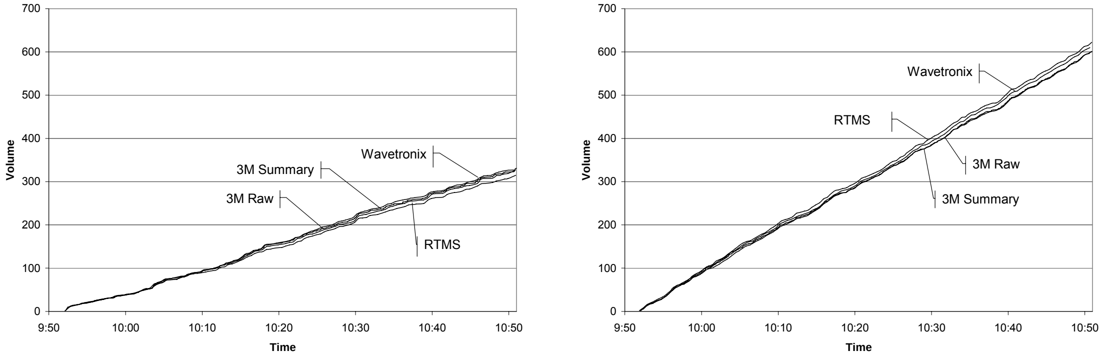
5.1.6. Occupancy Questionable

The data set taken on May 17, 2006 was a one hour set. Initially it was to be used to determine if the RTMS unit replacement had been successful. The data was analyzed using the volume and cumulative sensor ‘on-time’ metrics. The cumulative volume graphs, shown in Figure 5.3 indicate generally good agreement between all the sensors, with the exceptions being a slight undercounting by the RTMS unit in the SB Driving Lane (Figure 5.3,a) and the Wavetronix Smartsensor exception being a slight over counting in the SB Passing Lane (Figure 5.3,b).



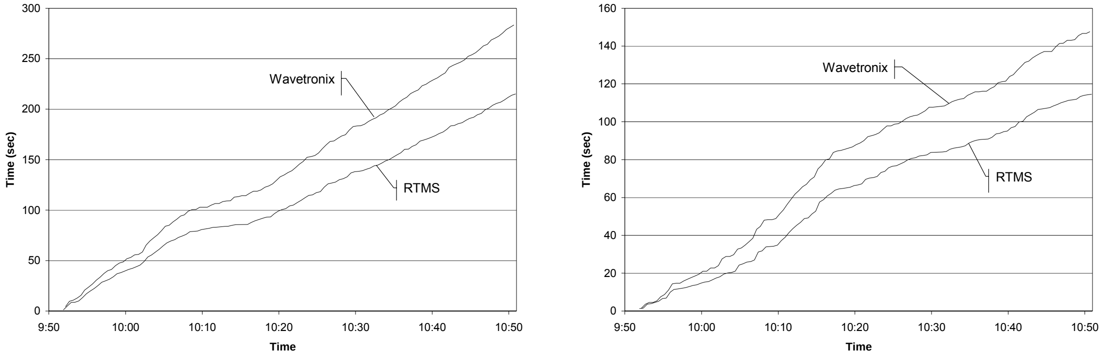
a) SB Driving Lane b) SB Passing Lane



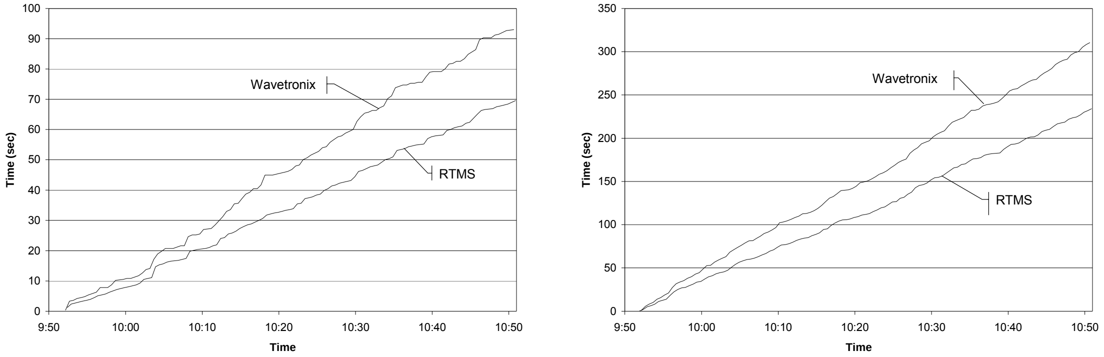
c) NB Passing Lane d) NB Driving Lane

Figure 5.3 May 17, 2006 Cumulative Volume vs. time plots from I-65 @ mm 128 site (0950 to 1050)

The cumulative ‘on-time’ metric was evaluated for the RTMS and Wavetronix Smartsensor in each lane of the mm 128 site. The graphs are shown in Figure 5.4 - a,b,c,d), and indicate a clear trend that the Wavetronix Smartsensor was providing a larger occupancy value than the RTMS unit. This analysis led to further contact with vendor technical representatives and the decision to meet on-site with Chip Lang (Traffic Control Corporation) the Wavetronix technical representative on May 26, 2006.



a) SB Driving Lane b) SB Passing Lane



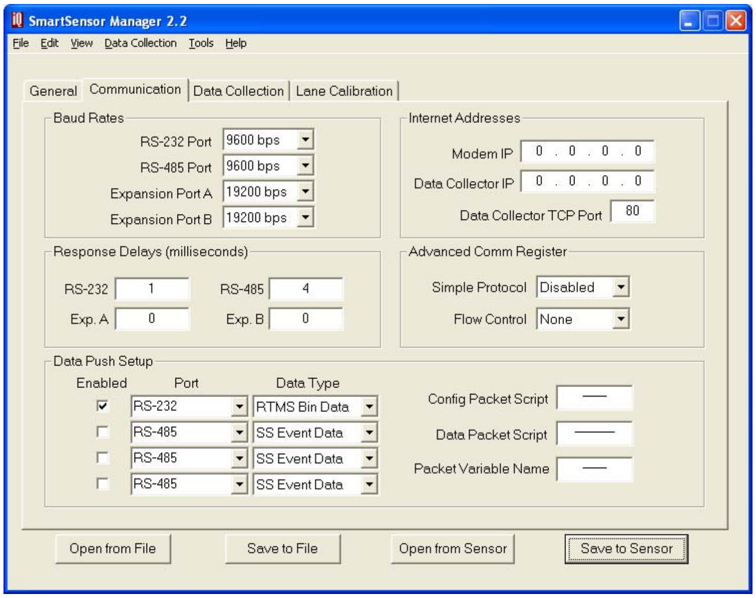
c) NB Passing Lane d) NB Driving Lane

Figure 5.4 May 17, 2006 Cumulative ‘On-Time’ vs. time plots from I-65 @ mm 128 site (0950 to 1050)

5.1.7. Site Visit for Occupancy Investigation

A site visit to the mm 128 site was made on May 26, 2006 to investigate the source of the occupancy difference between the Wavetronix Smartsensor and the RTMS unit. The Smartsensor was accessed using the Smartsensor Manager 2.2 interface program, and several settings were changed. The setting modifications are listed in Table 5.2. In an attempt to verify the settings in the RTMS setup program and ensure that the settings were similar the RTMS unit was accessed using the WinRTMS program. A sample set of data collected to check the results of the changes. It was later determined that the RTMS unit's data was compromised by accessing the unit. The graphs for the May 26, 2006 data set are shown in Figure 5.5, and indicate a large discrepancy between the RTMS cumulative volume and the Wavetronix and Microloop cumulative volume for all lanes at the mm 128 site. It was later determined that the firmware on the new RTMS unit was upgraded and was not compatible with the WinRTMS version used during the site visit. The data corruption issue was reported to EIS. An upgrade version of WinRTMS was later used to perform a self test on the RTMS unit and a microwave fault was detected, necessitating replacement of the unit.

Table 5.2 Wavetronix Smartsensor Setting Changes Made on May 26, 2006



Baud Rates

RS-232 Port: 9600 bps
RS-485 Port: 9600 bps
Expansion Port A: 19200 bps
Expansion Port B: 19200 bps

Internet Addresses

Modem IP: 0 . 0 . 0 . 0
Data Collector IP: 0 . 0 . 0 . 0
Data Collector TCP Port: 80

Response Delays (milliseconds)

RS-232: 1
RS-485: 4
Exp. A: 0
Exp. B: 0

Advanced Comm Register

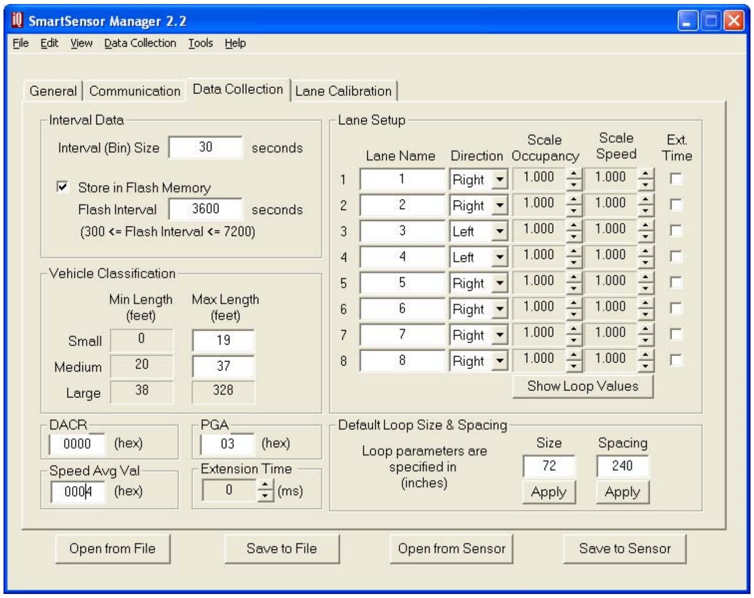
Simple Protocol: Disabled
Flow Control: None

Data Push Setup

Enabled	Port	Data Type
☑	RS-232	RTMS Bin Data
☐	RS-485	SS Event Data
☐	RS-485	SS Event Data
☐	RS-485	SS Event Data

Config Packet Script: —
Data Packet Script: —
Packet Variable Name: —

a) Changed “Simple Protocol” enable to disable



Interval Data

Interval (Bin) Size: 30 seconds
☑ Store in Flash Memory
Flash Interval: 3600 seconds
(300 <= Flash Interval <= 7200)

Vehicle Classification

	Min Length (feet)	Max Length (feet)
Small	0	19
Medium	20	37
Large	38	328

DACR: 0000 (hex)
PGA: 03 (hex)
Speed Avg Val: 0004 (hex)
Extension Time: 0 (ms)

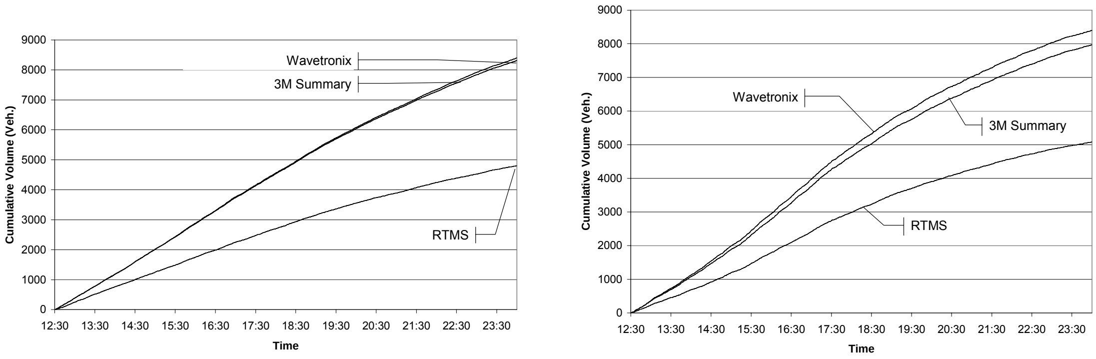
Lane Setup

	Lane Name	Direction	Scale Occupancy	Scale Speed	Ext. Time
1	1	Right	1.000	1.000	☐
2	2	Right	1.000	1.000	☐
3	3	Left	1.000	1.000	☐
4	4	Left	1.000	1.000	☐
5	5	Right	1.000	1.000	☐
6	6	Right	1.000	1.000	☐
7	7	Right	1.000	1.000	☐
8	8	Right	1.000	1.000	☐

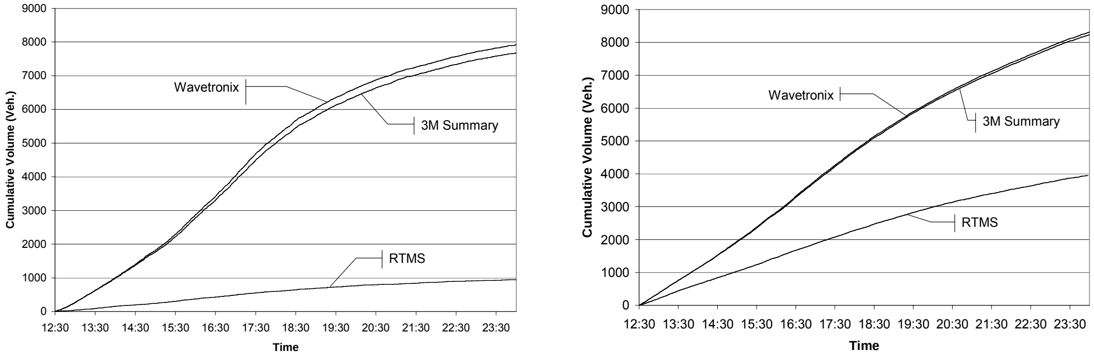
Default Loop Size & Spacing

Loop parameters are specified in (inches)
Size: 72
Spacing: 240

b) Changed FFFF to 0004 on “Speed Avg. Val”



a) SB Driving Lane b) SB Passing Lane



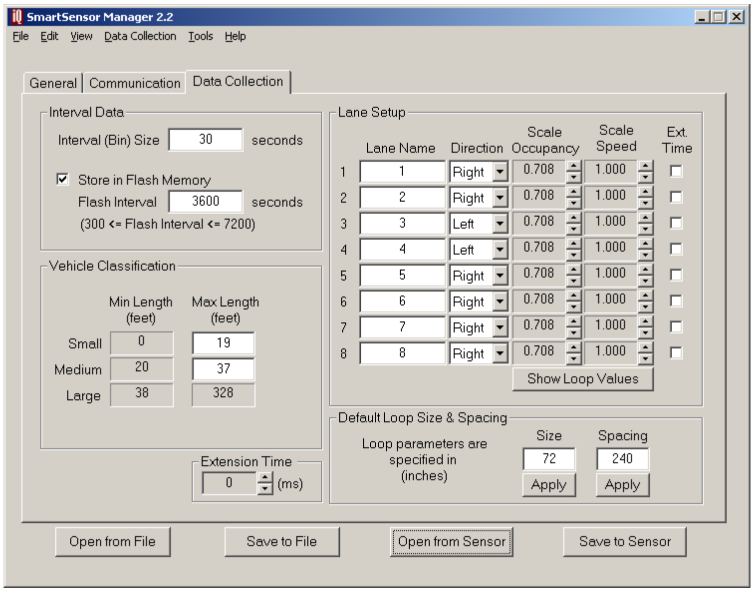
c) NB Passing Lane d) NB Driving Lane

Figure 5.5 May 26 2006 Cumulative 'On-Time' vs. time plots from I-65 @ mm 128 site (1230 to 2400)

5.1.8. Wavetronix Smartsensor Occupancy Scaling

After reviewing several data collection periods, a recommendation was made by Wavetronix technical personnel to modify the scale occupancy from 1.000 to 0.708. This modification was made on June 11, 2006. The setting changes are shown in Table 5.3.

Table 5.3 Wavetronix Smartsensor Setting Changes Made on June11, 2006



Interval Data

Interval (Bin) Size 30 seconds

☑ Store in Flash Memory

Flash Interval 3600 seconds

(300 <= Flash Interval <= 7200)

Vehicle Classification

	Min Length (feet)	Max Length (feet)
Small	0	19
Medium	20	37
Large	38	328

Extension Time 0 (ms)

Lane Setup

	Lane Name	Direction	Scale Occupancy	Scale Speed	Ext. Time
1	1	Right	0.708	1.000	☐
2	2	Right	0.708	1.000	☐
3	3	Left	0.708	1.000	☐
4	4	Left	0.708	1.000	☐
5	5	Right	0.708	1.000	☐
6	6	Right	0.708	1.000	☐
7	7	Right	0.708	1.000	☐
8	8	Right	0.708	1.000	☐

Default Loop Size & Spacing

Loop parameters are specified in (inches)

Size 72

Spacing 240

a) Changed Scale Occupancy to 0.708 from 1.000

5.1.9. RTMS Unit Replaced

On July 5, 2006 the RTMS unit was tested and replaced. A two hour data set was collected to verify the operation of the unit. The results of the initial test indicated that the replacement was successful and data collection continued.

5.1.10. Brickyard 400 Traffic Event

The Brickyard 400 race event provided an opportunity to investigate the performance of the sensors at the test bed during potentially congested conditions. This data set was also one of the first which was analyzed in detail using the Microloop csv data along with the summary data from the sidefire radars. The RTMS unit was not providing data during this time period and was later power-cycled. Further analysis and discussion of the metrics for this event are in CHAPTER 7.

CHAPTER 6. I-65 @ MM128 DATA SET

6.1. Example Data from ITS Sensors

Data collected from the mm 128 site was used as part of the third step in the DMAIC process as shown in Figure 6.1. The analysis of data from the site was used to determine the root cause of sensor errors. Once the root cause of errors was determined, the next step in the process is to develop solutions to prevent the same type of errors in the future.

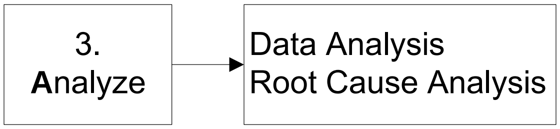


Figure 6.1 DMAIC Process – Analyze Step

6.1.1. Side-Fire Radar Data

The data from both the RTMS and Wavetronix sensors is provided in the same format, which provides the following information for each 30 second interval: interval volume, interval average speed, and interval sensor occupancy.

6.1.1.1. Explanation of Sidefire Radar Summary Data Format

The data for each sensor is placed in a separate file, with all files for a given time period having the same date and start time as part of their filenames. The file extension is different for each type of file, as shown in Table 6.1. For example 20060526_0930_ttyS6.eis would be a summary data file for the RTMS sensor starting at 9:30 AM on May 26, 2006. No information about the length of the data collection period is embedded in the filename, only the date that the data collection started and the time at which the file was created.

Table 6.1 File Naming Convention

Sensor	**File Name**		
	Summary Data	**Raw Data**	**Processed Data**
SB 3M Microloop/Canoga	ttyS4.3m	ttyS4.3mraw	ttyS4.3mcsv
NB 3M Microloop/Canoga	ttyS5.3m	ttyS5.3mraw	ttyS5.3mcsv
Wavetronix SmartSensor	ttyS6.eis	N/A	N/A
RTMS	ttyS7.wave	N/A	N/A

6.1.1.2. Wavetronix Smartsensor Data

The Wavetronix Smartsensor data file provides interval summary data for eight lanes by default. Since the mm128 site on I-65 has two travel lanes in each direction, the Smartsensor will recognize these lanes as 1,2,3 and 4, and provide interval data accordingly. Lanes 5,6,7 and 8 will always be reported as the default value by the Smartsensor. An example of Smartsensor data is shown in Table 6.2. The tabulated data with column headers is shown in Table 6.3. Notice that the data for lanes 5,6,7 and 8 is repeating default data, which is caused by the lanes not being recognized by the sensor. The data for Lane 3 in Table 6.3 also provides default values, due to the interval volume being zero. Typical default data correlated to the corresponding cause is shown in detail in Table 6.4.

Table 6.2 Example of Wavetronix SmartSensor Output File Data

```
2006-05-26,12:30:31,1,2,3000,66
2006-05-26,12:30:31,2,1,0,76
2006-05-26,12:30:31,3,0,0,149
2006-05-26,12:30:31,4,4,8000,62
2006-05-26,12:30:31,5,255,62000,30
2006-05-26,12:30:31,6,255,62000,30
2006-05-26,12:30:31,7,255,62000,30
2006-05-26,12:30:31,8,255,62000,30
```

Table 6.3 Parsed Wavetronix SmartSensor Data

Line	**Date**	**AFP Time**	**Lane Number**	**Volume (/30s)**	**Occupancy (%)**	**Avg. Speed (mph)**
1	2006-05-26	12:30:31	1	2	3.00	66
2	2006-05-26	12:30:31	2	1	0	76
3	2006-05-26	12:30:31	3	0	0	149
4	2006-05-26	12:30:31	4	4	8.00	62
~~5~~	~~2006-05-26~~	~~12:30:31~~	~~5~~	~~255~~	~~62.00~~	~~30~~
~~6~~	~~2006-05-26~~	~~12:30:31~~	~~6~~	~~255~~	~~62.00~~	~~30~~
~~7~~	~~2006-05-26~~	~~12:30:31~~	~~7~~	~~255~~	~~62.00~~	~~30~~
~~8~~	~~2006-05-26~~	~~12:30:31~~	~~8~~	~~255~~	~~62.00~~	~~30~~

Table 6.4 Wavetronix SmartSensor Default Data Values

Cause of Default Value	Volume	Occupancy	Speed
No Lane Recognized	255	62000	30
No Interval Volume Reported	0	0	149

6.1.2. 3M Microloop Sensor Data

6.1.2.1. Microloop Summary Data

Microloop sensor data is provided in summary format, an example is shown in Table 6.5. The parsed data with column headers is shown in Table 6.6.

Table 6.5 Example of 3M Microloop Summary Data

```
2006-05-26,144232,1,3,0,83
2006-05-26,144232,2,3,0,73
2006-05-26,144302,1,2,0,83
2006-05-26,144302,2,2,0,73
2006-05-26,144332,1,5,0,86
2006-05-26,144332,2,6,0,79
2006-05-26,144402,1,10,0,82
```

Table 6.6 Parsed 3M Microloop Summary Data

Line	Date	AFP Time	Lane Number	Volume (/30s)	Occupancy (%)	Avg. Spd. (mph)
1	2006-05-26	14:42:32	1	3	0	83
2	2006-05-26	14:42:32	2	3	0	73
3	2006-05-26	14:43:02	1	2	0	83
4	2006-05-26	14:43:02	2	2	0	73
5	2006-05-26	14:43:32	1	5	0	86
6	2006-05-26	14:43:32	2	6	0	79
7	2006-05-26	14:44:02	1	10	0	82
8	2006-05-26	14:44:02	2	7	0	83

6.1.2.2. Microloop Raw Data

The data provided by the Canoga Detector cards is initially provided in binary format. A utility program was created by Iron Mountain Systems, Inc. to convert the raw 3M data into a comma delimited text file format. An example of the imported data from the comma separated value (csv) file is shown in . A data record is composed of one line of data, as shown in Table 6.6. The first column provides the date that the data record was taken in. The second column is the Aries Field Processor (AFP) time, to which the data record corresponds. The third column is an identifier number that increases with time and is used to make each line of data unique. The fourth column is the duration that the detector sensed the vehicle. The fifth column is the ‘relative time’ in milliseconds that the detection occurred, using a 32 bit counter. The sixth column is the relative detector count using an 8 bit counter. For channels 2, 3 and 4 columns 4, 5 and 6 in Table 6.6 would be repeated as columns: 6,7,8; 9,10,11; 12,13,14.

Table 6.7 Example of Imported Microloop Data

Identifiers			**Channel 1**		
(1)	(2)	(3)	(4)	(5)	(6)
Date	Time	Line #	Dur	Det. Count	Veh
8/6/2006	19:30:00	1007432	105	2058134698	13
8/6/2006	19:30:00	1007435	105	2058134698	13
⋮	⋮	⋮	⋮	⋮	⋮
8/6/2006	19:30:01	1007505	81	2058138609	14
8/6/2006	19:30:01	1007508	81	2058138609	14
⋮	⋮	⋮	⋮	⋮	⋮
8/6/2006	19:30:04	1007532	139	2058139924	15
8/6/2006	19:30:04	1007535	139	2058139924	15
⋮	⋮	⋮	⋮	⋮	⋮
8/6/2006	19:30:08	1007641	139	2058144230	16
8/6/2006	19:30:08	1007644	139	2058144230	16

6.2. Data Analysis Methodology

The data captured in the summary file format was readily available for analysis. The analysis was performed by importing the summary files into Microsoft Excel, as comma delimited text files. However, the comma delimited text file produced as a result of the raw Microloop data file was much larger, and the maximum amount of data that could be analyzed in MS Excel from the raw Microloop data was from a two hour interval. Thus all of the analysis of the raw Microloop data is limited to two hour intervals. The algorithms used for processing the comma delimited value data files for the Microloops are shown in Figure 6.2 and Figure 6.3. Note that one limitation of the specified algorithm is that the use of Microloop data in an unprocessed format relies on either using the lead or lag detector as trigger for calculating speeds, so that if cross-lane detection occurs on only one sensor the algorithm will provide an erroneous value for the speed, which can be either negative or positive. The speeds are used to calculate the number of vehicles within an interval, and can alter AEVL values in two ways. Firstly the erroneous speeds are averaged within the interval for use in the numerator of the AEVL test, and any erroneous values are counted as vehicles within the interval and influence the equivalent hourly volume, which is the denominator of the AEVL test.

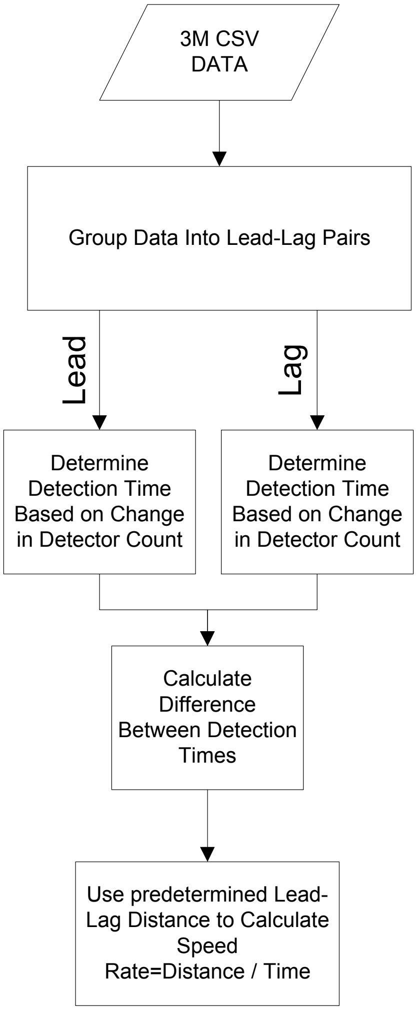


Figure 6.2 Microloop CSV file speed processing algorithm

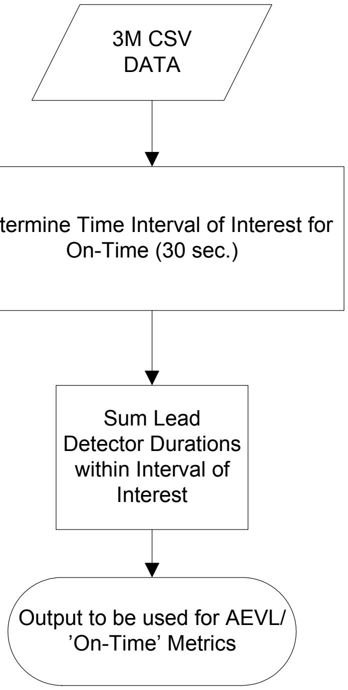


Figure 6.3 Microloop CSV file 'On-Time' and AEVL input processing algorithm

6.3. Performance Metrics using mm 128 data

6.3.1. Volume Comparison

The first performance metric evaluated at the test site was the volume comparison. Data was collected at various times throughout the project duration, and selected subsets of data were compared to volume data confirmed by groundtruthing the data set. The evaluation of this metric is visually performed to assess how accurately the sensors are detecting vehicles. Discrepancies between independent, but co-located sensor data indicate a sensor problem. Figure 6.4 illustrates a case with very good agreement between sensors. This graph shows that the final groundtruth cumulative volume (1883 vehicles) falls between the traces of the Wavetronix (1906 vehicles) and the 3M Microloop (1883 vehicles) final cumulative volumes. This indicates that both the sensors are providing data classified as "Best" according to the ITS America data quality guidelines, as shown in

Table 2.1, since they are within ±5% of the groundtruth volume.

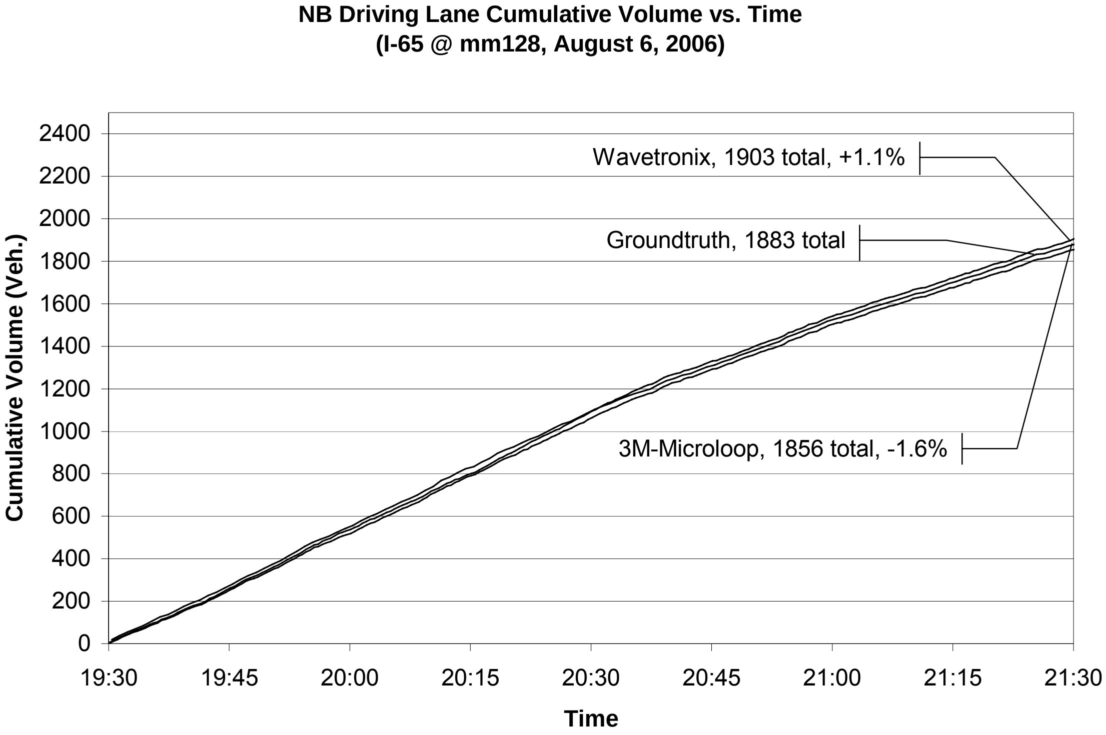


Figure 6.4 Cumulative Volume Comparison indicating "Best" Data Quality Level, per ITS American Data Quality Guidelines

Conversely, when the cumulative volume traces of different sensors diverge over time there is a strong indication that the data is suspect. This is the case in Figure 6.5, where one of the traces lags significantly over the data collection period. Upon closer inspection the final cumulative volume of the RTMS unit is over 3,500 vehicles less than either the Wavetronix or 3M Microloop final cumulative volumes. The agreement between the traces of the Wavetronix and

3M Microloop data indicates that the RTMS unit was likely not providing good data. The result of this data analysis was used as a basis for further investigation into the data quality of the RTMS unit, and ultimately to replacement by EIS.

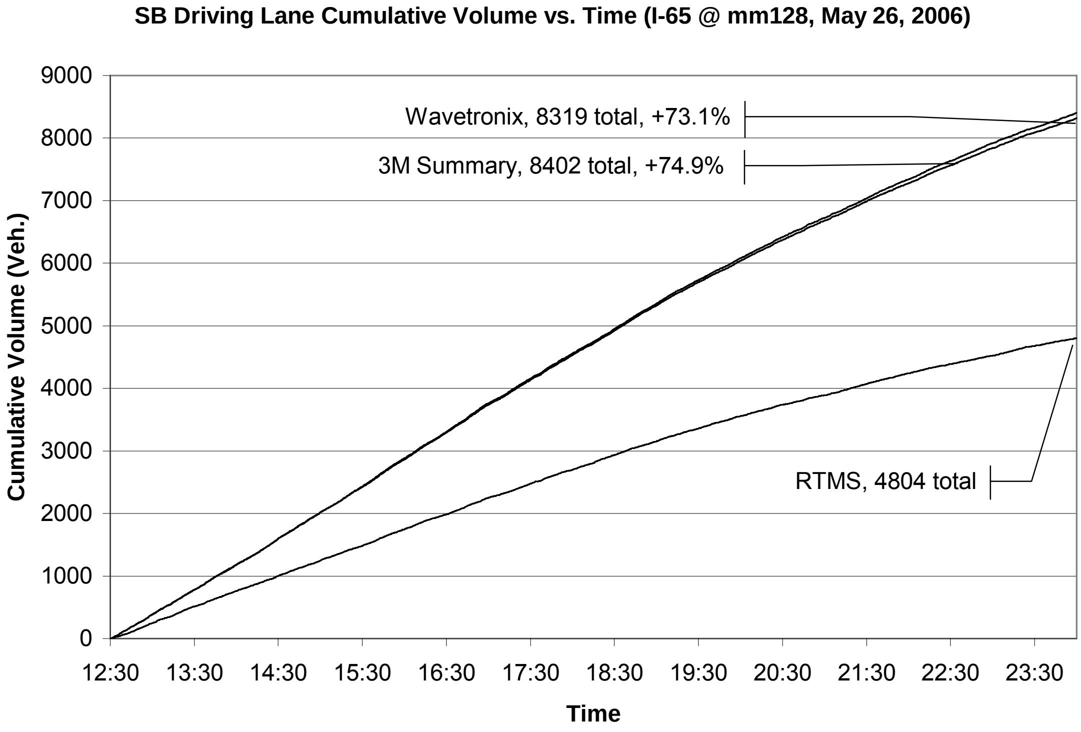


Figure 6.5 Cumulative Volume Comparison indicating that further investigation of RTMS data is necessary

6.3.2. Speed Comparison

Comparison of average interval speed is also useful to screen sensor data. In general this metric is not as powerful as the cumulative volume comparison because the sensors are sampling different time intervals and are not located in the same location on the freeway section. There is a minimum distance that the sensors must be separated in order to prevent interference. This is illustrated in Figure 4.2 (b), as the Wavetronix Smartsensor and RTMS sensors are mounted on wooden poles at opposite ends of the mm128 site. However this metric can provide additional information as to whether a sensor is providing good data. Due to the inherent noisiness of the sensor data a comparison of the general trends of two independent sensor outputs is critical to determining potential data quality problems. Typical sensor noise is shown in Figure 6.6, as the average speed is not constant and ranges in general from 45 to 75 mph.

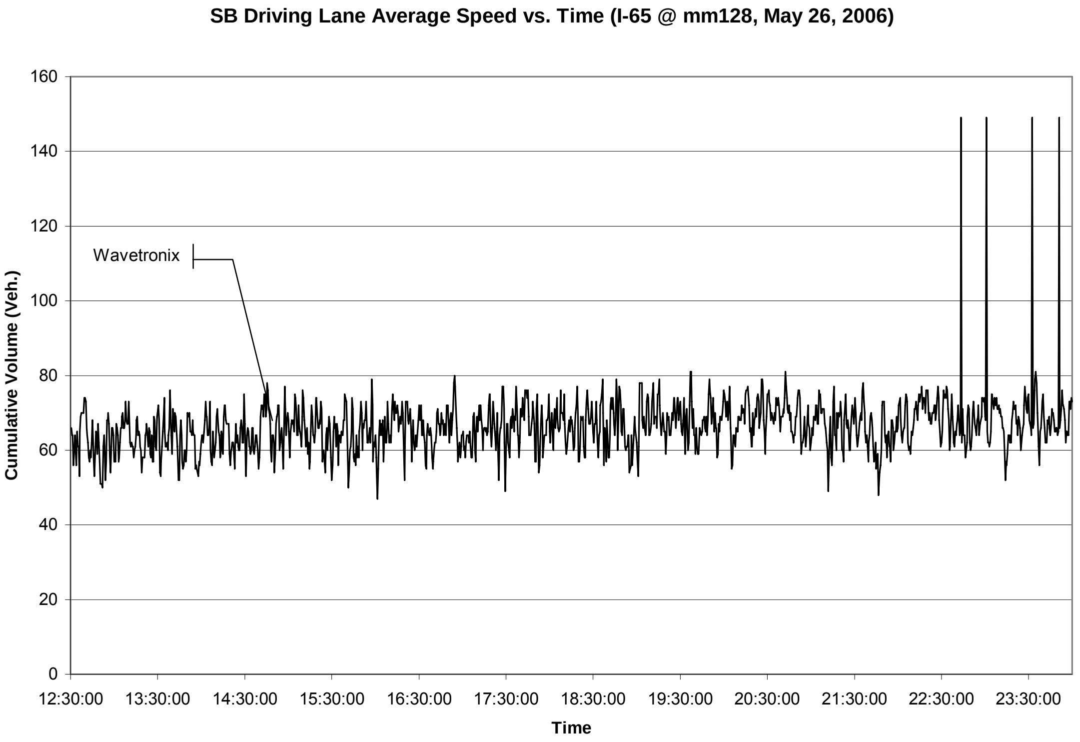


Figure 6.6 Average Speed vs. Time Plot showing example of sensor noise

The side by side comparison of two or more independent average speed traces, such as shown in Figure 6.7, indicates a discrepancy in the average speeds. The default speed, reported by both the Wavetronix and the RTMS unit, when no vehicles are present in an interval is 149 mph. As shown in Figure 6.7, the RTMS unit is reporting many more intervals with 149 mph as the average speed, which is the default value for speed when no vehicles are detected in an interval.

This further corroborates the cumulative volume chart shown in Figure 6.5, as more intervals with zero volume have lead to the RTMS cumulative volume being much lower than the other sensors cumulative volumes. Further visual analysis of Figure 6.7 indicates that the typical noise that is expected for this type of data is not present and the average speed trace for the RTMS unit is distinctly different in appearance from the Wavetronix average speed trace. Therefore according to the speed comparison metric the RTMS sensor would be suspect for the data set shown in Figure 6.7 due to the following:

- Lack of agreement between two speed traces
- Much higher incidence of default speed values (149mph)

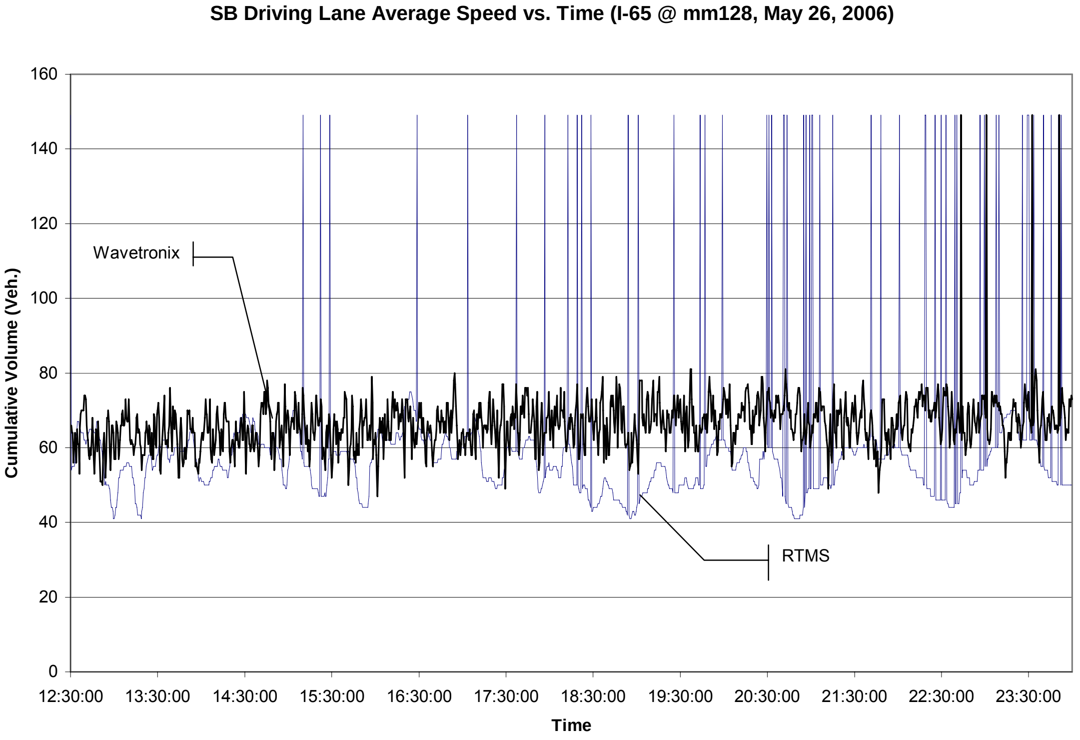


Figure 6.7 Average Speed vs. Time Plot showing disagreement between RTMS and Wavetronix data

The average speed is also sensitive to the sensor's ability to accurately measure time. This is shown in Figure 6.8, as the average speed traces between the Wavetronix and 3M Microloop are much closer together in the time period between approximately 2010 and 2040. The traces show more variation at higher speeds. This is due to the speed being a function of the sensors ability to determine presence within the detection zone, and the combined effect of sensor occupancy decreasing with an increase in speed. This is further discussed in the next section.

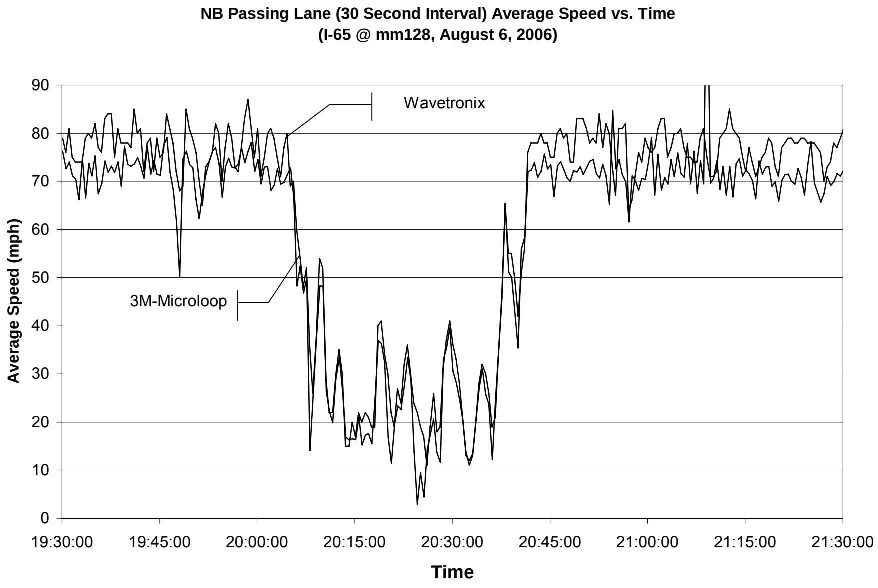


Figure 6.8 I-65 @ mm128 NB Passing Lane Speed Comparison

6.3.2.1. Speed Resolution of Microloop Sensor System

The speed resolution level that a sensor is able to produce is directly related to the sensors ability to determine presence within the detection zone. In the case of the Microloop/Canoga Vehicle Detection system the speed resolution is limited due to the interval time between detector card checks for sensor presence (18). This is also known as the 'scan time' of the detector card which is related to the bridge time and sensor sensitivity. The scan time is a constant value that affects the resolution of the sensor output and in effect filters the millisecond reporting to whatever level is set for the scan time. The scan time has a larger effect on faster vehicles, which have smaller inter-detector time. This is due to the inverse relationship of inter-detector travel time and speed as show in the following equation:

$$V = \frac{\text{Distance}}{\text{Time}} \qquad \text{Equation 6.1}$$

This is due to the fact that as the inter-detector time decreases the scan time becomes a larger percent of the inter-detector travel time. An example using theoretical values is shown in Table 6.8.

Table 6.8 Effect of Scan Time on Speed

Speed	**Speed Trap Travel Time (assuming 20 ft. effective sensor spacing)**	**Scan Time as % of Travel Time (scan time assumed as 10 milliseconds)**
55 mph (80.7 ft/sec)	248 milliseconds	4.0%
65 mph (95.3 ft/sec)	210 milliseconds	4.8%
75 mph (110.0 ft/sec)	182 milliseconds	5.5%

The effect of scan time on speed resolution is shown in Figure 6.9, as the higher speeds are separated by larger values than the lower speeds. This trend also indicates that the lower speeds are less affected by the scan time since the travel time between sensors is greater and the effect of the scan time decreases.

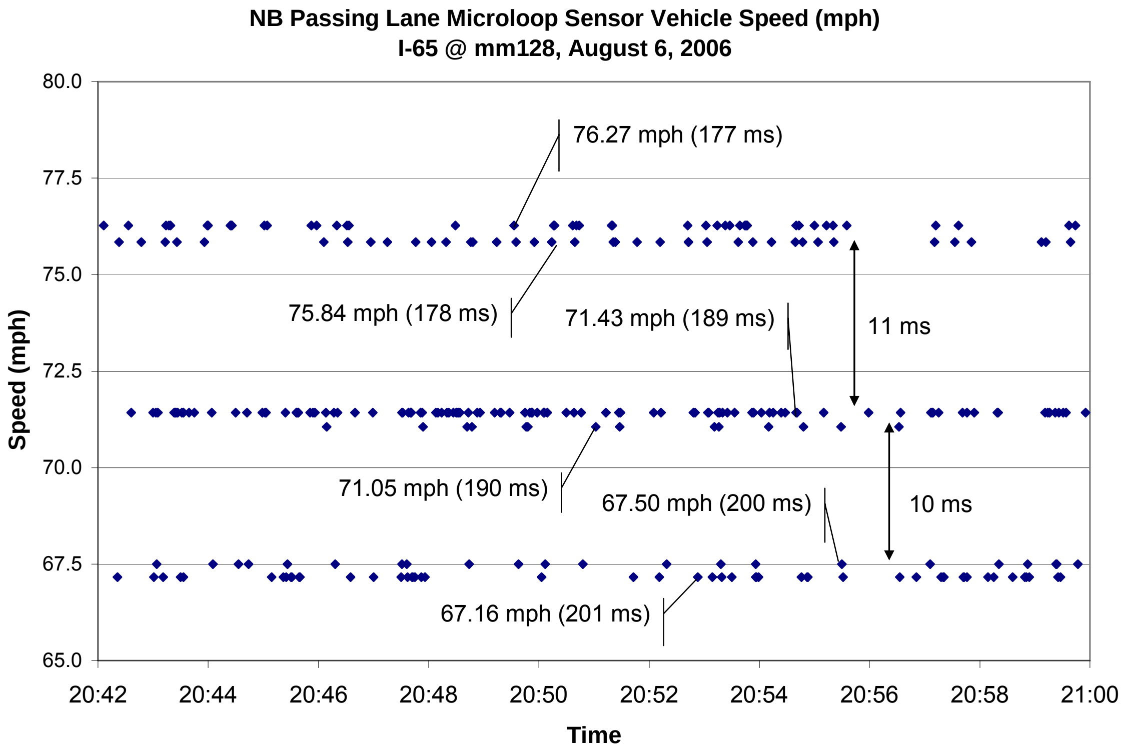


Figure 6.9 Speed Resolution (Resolution Decrease with Speed Increase)

An example of speeds calculated from the delimited text files along with inter-detector time is shown in . The speeds correspond to the Northbound Passing Lane at the mm 128 site on I-65.

Table 6.9 Microloop Calculated Speed and Time Measure Relationship for NB Passing Lane of I-65 @ mm 128 site (19.8 ft sensor spacing)

Calculated Speed (mph)	Time Measure (millisecond)
87.66	154
87.10	155
81.82	165
81.33	166
76.27	177
75.84	178
71.43	189
71.05	190
67.50	200
67.16	201
63.78	212
63.38	213
60.27	224
60.00	225
57.45	235
57.20	236

Calculated Speed (mph)	Time Measure (millisecond)
54.66	247
54.44	248
52.33	258
52.12	259
50.00	270
49.82	271
47.87	282
47.70	283
46.08	293
45.92	294
44.26	305
44.12	306
42.59	317
42.45	318
41.16	328
41.03	329

6.3.3. Occupancy Comparison

The occupancy metric is directly related to the amount of time that each sensor has detected a vehicle over the interval time. As such, the tendency of the trace is to steeply increase as the interval volume increases and/or vehicle speeds decrease. This is evident in Figure 6.10, as all three traces steeply incline during the period between approx. 2010 and 2040. An examination of the video for this time period clearly shows an increase in volume and decrease in vehicle speed, thus a large increase in interval on-time is expected. The agreement between all three trace for the time period shown in Figure 6.10 indicates that the data quality is acceptable.

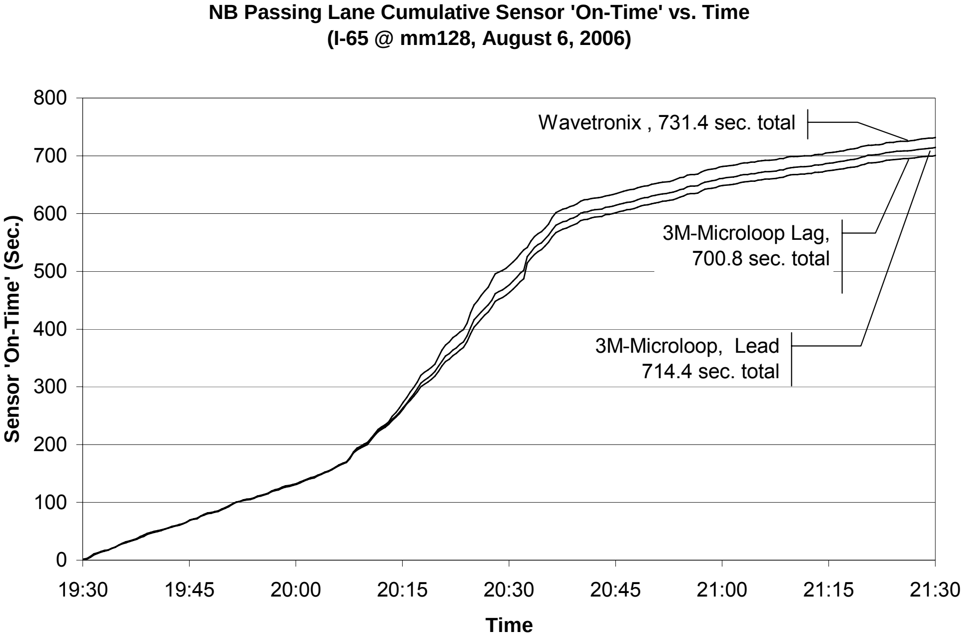


Figure 6.10 Example of good agreement between cumulative sensor ‘On-Time’ traces

Poor agreement between data traces is shown in Figure 6.11, as the final cumulative on-time value for the Wavetronix Sensor is more than 285% the magnitude of the RTMS sensor’s final value.

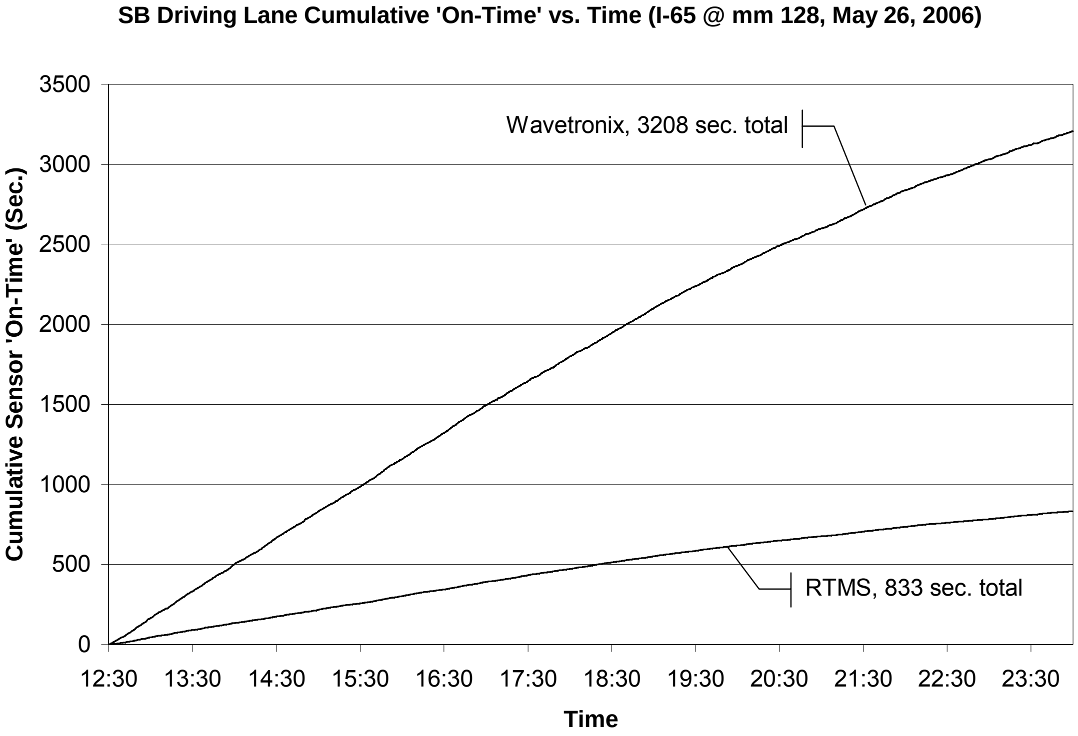


Figure 6.11 Example of poor agreement between cumulative sensor ‘On-Time’ traces

6.3.4. AEVL Test

The AEVL test provides the ability for the data to be preliminarily screened without having to compare the other three metrics among sensors. Since the test is composed of the other three measures it can provide an idea about the relative data quality that the sensor is providing. As discussed previously the AEVL test provides objective criteria for reviewing sensor data. If the Test values fall between the upper and lower bounds of 60 and 9 feet respectively then the data is generally considered to be acceptable. Such a case where the most of the AEVL test values fall within the test limits is shown in Figure 6.12. The AEVL test values in Figure 6.12 are from the same time period as the average speed vs. time plot shown in Figure 6.8. An interesting characteristic is that since the AEVL test value is a function of the three sensor outputs, the AEVL value can be used as an initial screening tool for sensor health monitoring.

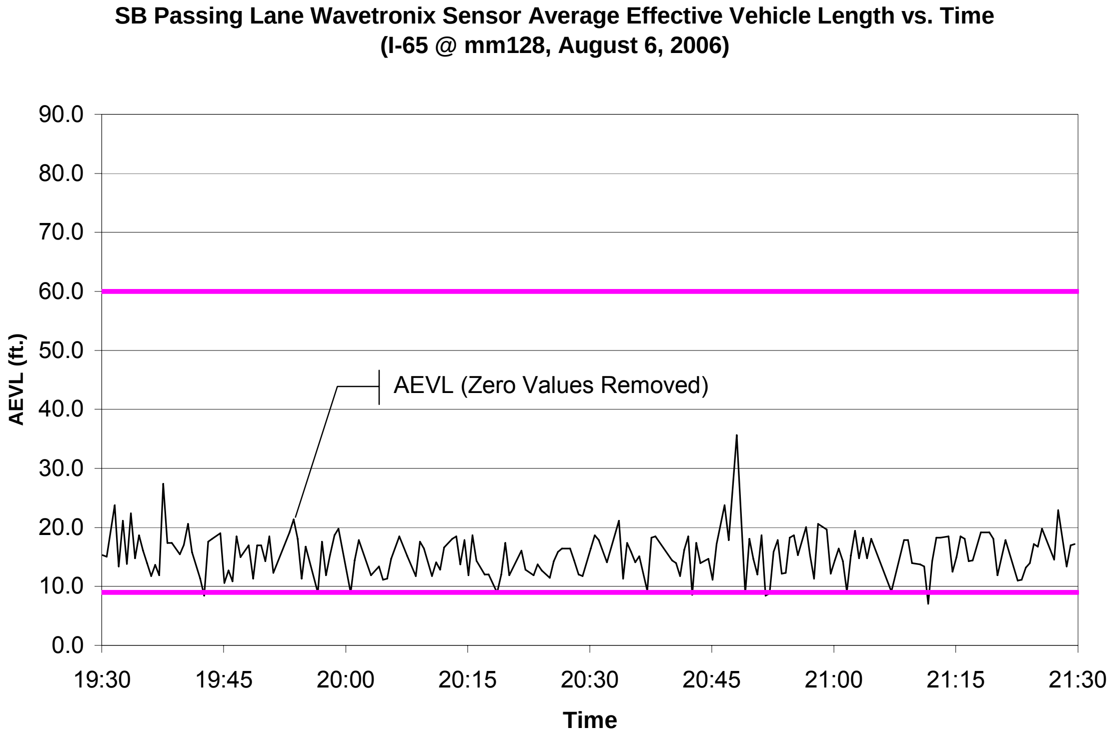


Figure 6.12 I-65 @mm128 SB Passing Lane AEVL Test vs. Time

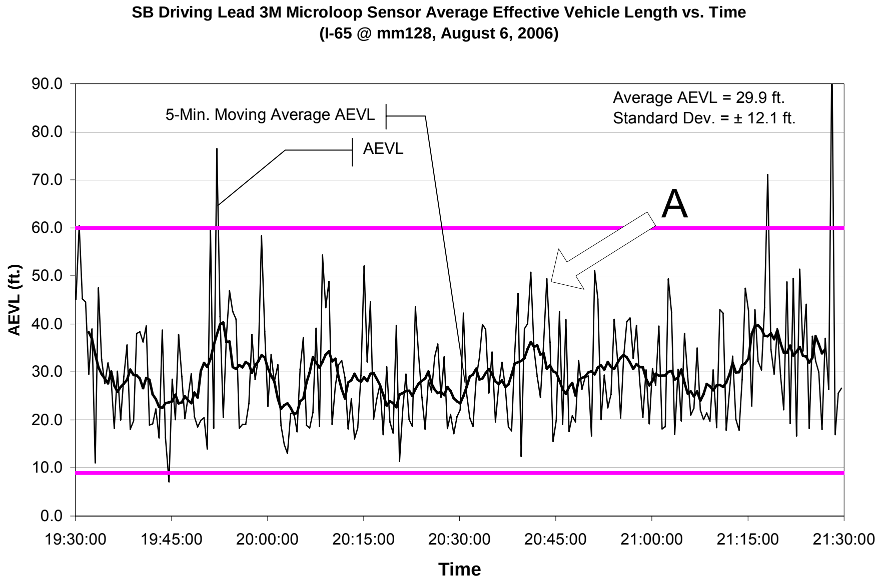
6.3.5. AEVL with Microloop CSV Data

The AEVL test for the Microloop sensor lead/lag pairs offers the chance to perform ongoing quality control monitoring due to the fact that the two sensors are independent of each other. The AEVL calculation for Microloop sensors in this project was performed for both the lead and lag sensors. Any difference between the two values can be attributed to the difference in Sensor Occupancy between the lead and lag sensors. All other input values for AEVL calculation are constant, since the average speed is computed using the number of reported speeds determined by both sensors, and the interval volume is calculated by summing the number of reported speeds in the interval. One anomaly that can be detected by comparing the AEVL graphs for lead/lag sensor pairs is when one sensor continues to send a call to the detector when no vehicles are present, as shown in Figure 6.13 for the interval ending at 20:44:35 (Point A). The values for AEVL test and corresponding interval sensor ‘on-time’ is reported in Table 6.10.

Table 6.10 Table of AEVL Values, Sensor ‘On-Time’, and calculations for the interval ending at 20:44:35 on August 6, 2006 (I-65 @ mm128 site)

Sensor	AEVL Calculated Value	Interval Sensor ‘On-Time”
SB Driving Lane Lead Microloop	$\frac{(5280)*(63.4mph)*(0.045)}{(120)*8} =$ 15.5 feet	1.336 seconds
SB Driving Lane Lag Microloop	$\frac{(5280)*(63.4mph)*(0.441)}{(120)*8} =$ 153.6 feet	13.225 seconds

The corresponding shift of the SB Driving Lane Lag Microloop sensor trace can be visualized in Figure 6.14, as the two cumulative ‘on-time’ traces are closely parallel with each other and the sharp increase in the SB Driving Lane Lag sensor occurs at the same time.


SB Driving Lead 3M Microloop Sensor Average Effective Vehicle Length vs. Time
(I-65 @ mm128, August 6, 2006)

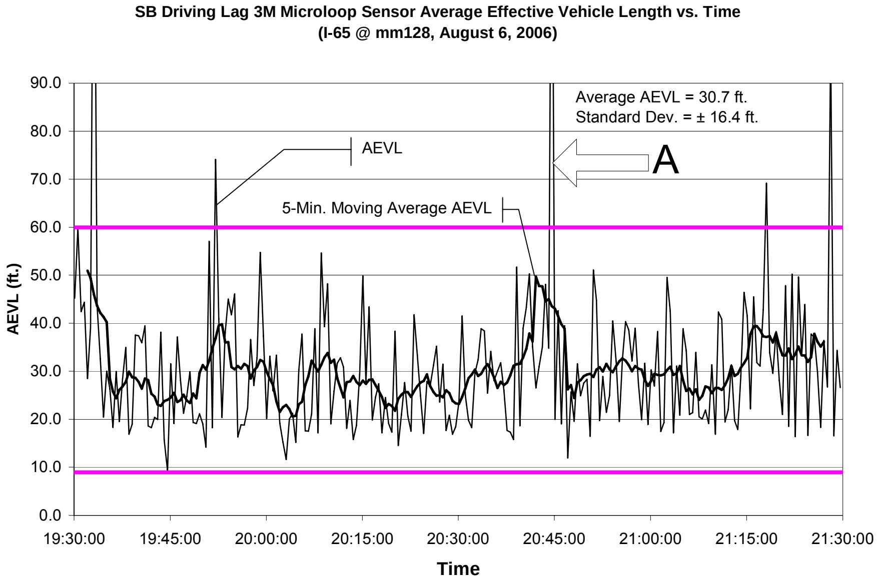

SB Driving Lag 3M Microloop Sensor Average Effective Vehicle Length vs. Time
(I-65 @ mm128, August 6, 2006)

Figure 6.13 Comparison of Lead and Lag AEVL graphs for Microloop sensor for August 6, 2006 on I-65 @mm 128 SB Driving Lane

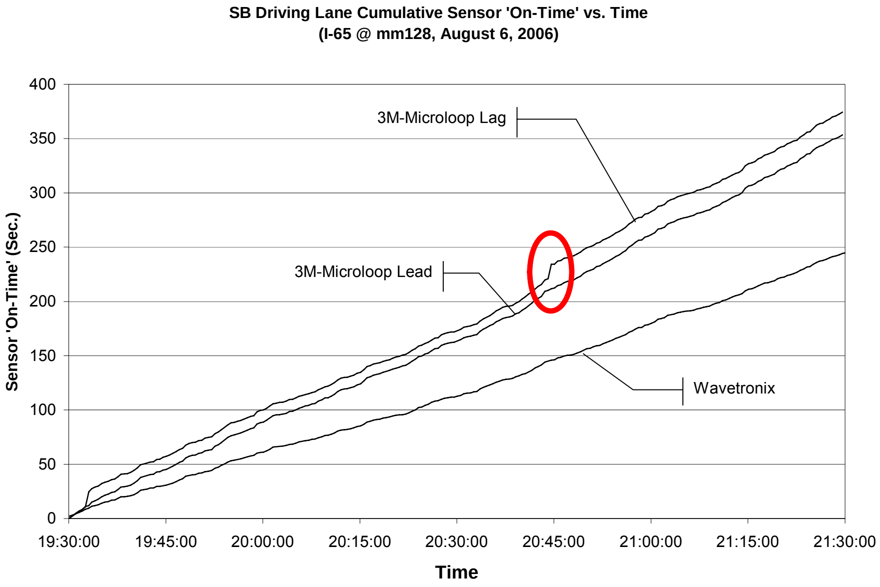


Figure 6.14 Cumulative Sensor ‘On-Time’ showing separation of traces due to stuck sensor

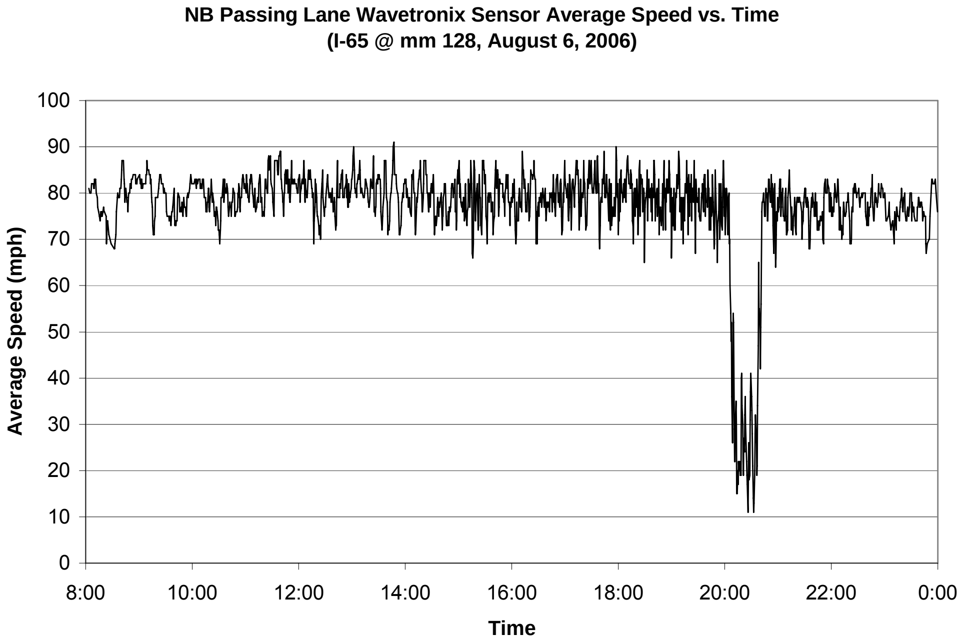
CHAPTER 7. AVERAGE EFFECTIVE VEHICLE LENGTH CASE STUDY

7.1. Introduction

The usage of AEVL metric as a tool for data quality monitoring is discussed in this Chapter. Since the usage of one metric as an initial test or tool to rank potential sensor data quality issues is desired, there is a need to further investigate the instances where the AEVL value calculated from the sensor interval data is outside the upper and lower limits. This chapter will provide a case study of several instances where the AEVL value falls outside the limits of 9 feet and 60 feet, which are conservative limits proposed in previous research (8).

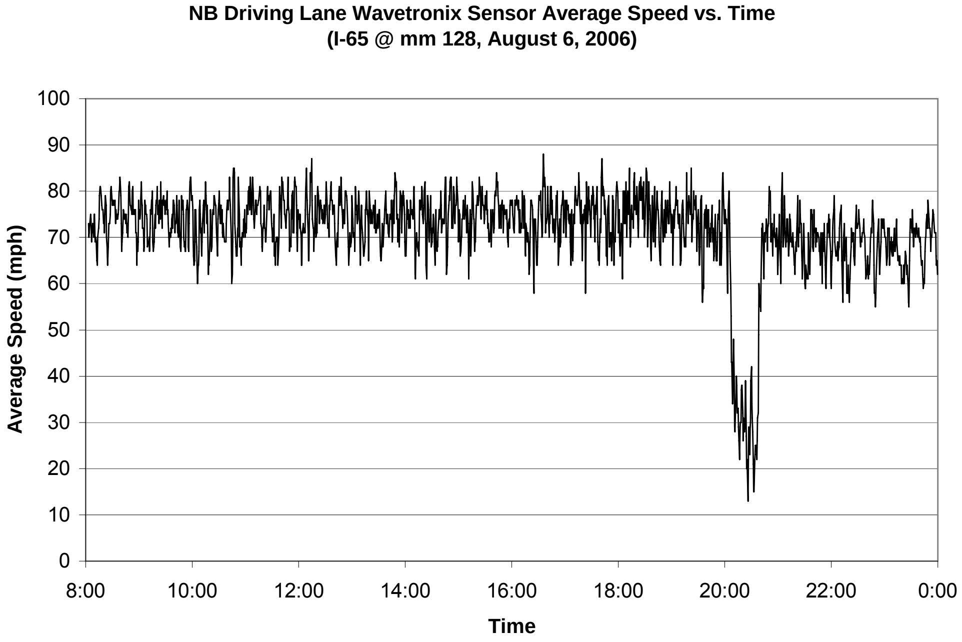
7.1.1. Brickyard Traffic Event Interval of Interest Determination

The Brickyard 400, which was held on August 6, 2006, provided an opportunity to examine varying levels of traffic flow at the test site on I-65 at the milemarker 128. The Microloop comma delimited sensor data time period of analysis is limited to a two hour interval, due to the use of MS Excel as an analysis tool. Data sets two hours had fewer than 65,536 lines, which is the maximum that MS Excel is able to process. Therefore it was important to determine the time period which had the heaviest volume. Therefore the speed vs. time plots were searched for possible slow downs that could be further analyzed for congestion occurrence. The lanes of interest were the northbound lanes, since the post event traffic would be exiting the greater Indianapolis using I-65 Northbound. The Northbound lane average speeds vs. time plots were analyzed and the time of interest was determined to be 7:30PM to 9:30PM. The plots used are shown in Figure 7.1.



NB Passing Lane Wavetronix Sensor Average Speed vs. Time
(I-65 @ mm 128, August 6, 2006)

a) NB Passing Lane Speed vs. Time



NB Driving Lane Wavetronix Sensor Average Speed vs. Time
(I-65 @ mm 128, August 6, 2006)

b) NB Driving Lane Speed vs. Time

Figure 7.1 Wavetronix Speed vs. Time Plots used to determine interval

7.1.2. Analysis

As noted previously the RTMS unit was not providing data during the time period of the Brickyard Event, therefore only the Wavetronix Smartsensor and Microloop sensors were analyzed. The AEVL plots were prepared for the time period between 7:30PM and 9:30PM. The resulting graphs were then further analyzed to determine if there were intervals for which the AEVL values calculated from the sensor interval data were outside the limits.

7.1.2.1. SB Driving Lane

The resulting plots are shown in Figure 7.2 and Figure 7.3 for the SB Driving Lane.

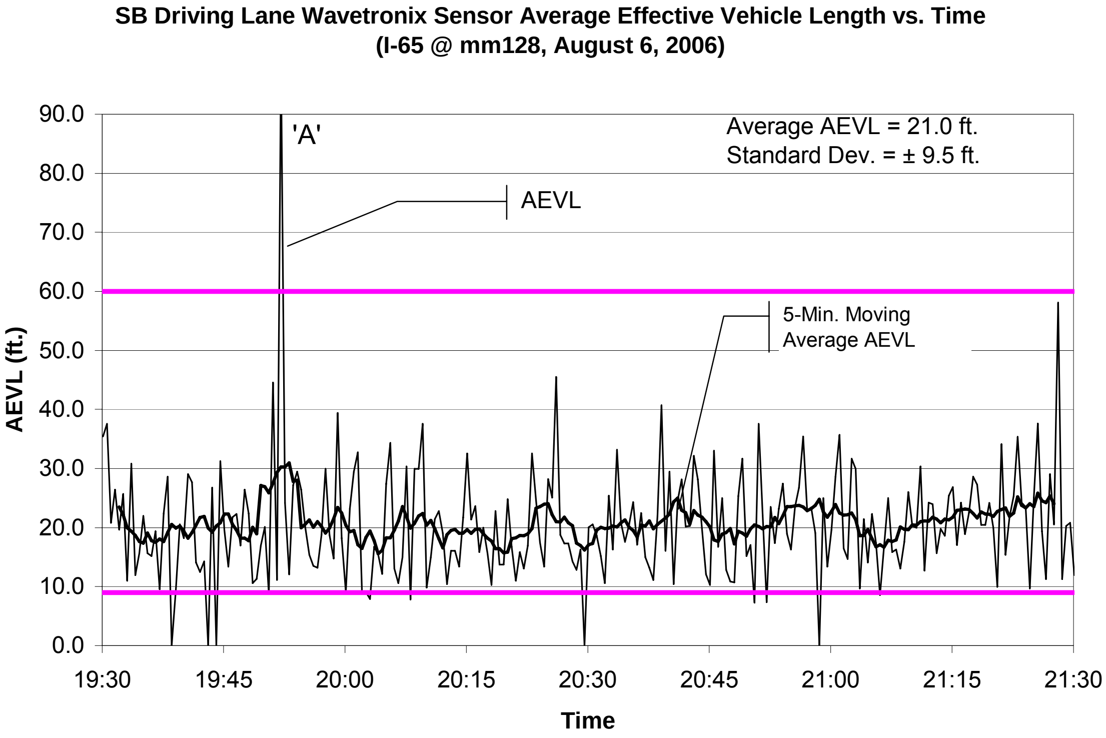
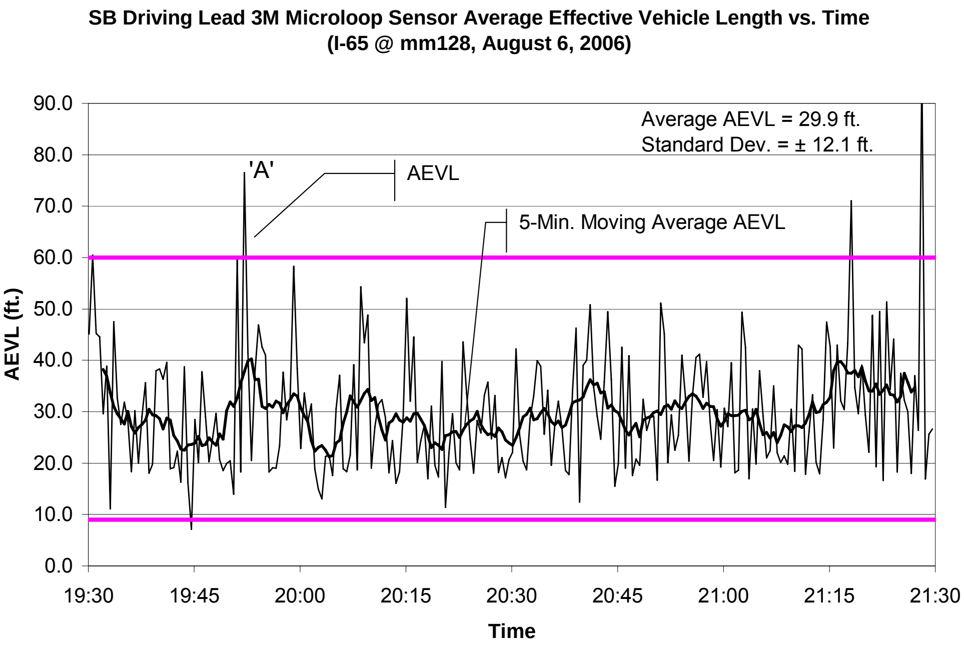
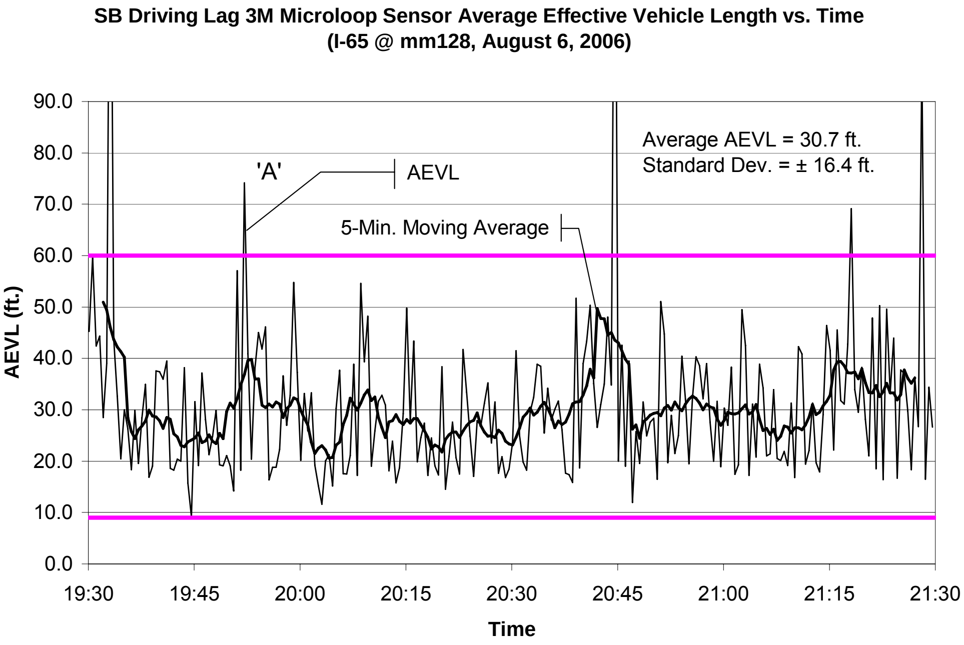


Figure 7.2 Wavetronix AEVL vs. Time Plot for
SB Driving Lane of I-65 @mm 128



a) SB Driving Lane Lead Microloop Sensor



b) SB Driving Lane Lag Microloop Sensor

Figure 7.3 Microloop AEVL vs. Time Plots SB Driving Lane of I-65 @mm 128

The point analyzed for the Southbound lane is noted as ‘A’ in Figure 7.2 and Figure 7.3. The interval values reported by the sensors, video groundtruthing and resulting calculated AEVL values are shown in Table 7.1.

Table 7.1 Interval Values and AEVL for Interval ending at 19:52:05 (SB Driving Lane)

Sensor	**Volume (vehicles/interval)**	**Occupancy (decimal)**	**Speed (mph)**	**Calculated/ Estimated AEVL**
Wavetronix	1	0.03	76	99.0 feet
Microloop Lead	1	0.024	71.6	76.5 feet
Microloop Lag	1	0.024	71.6	74.2 feet
Groundtruth	1	0.023 (est.)	76.1	77

Analysis of this time interval using the video determined that the AEVL calculated from the sensor data was reasonable. The only vehicle present in the SB Passing Lane during the interval in question was a Class 9 truck, with an estimated length of 75 feet. The estimated AEVL value of 77 feet was determined by adding an assumed detector length of 2 feet to the estimated truck length to estimate an interval AEVL, using the following formula:

$$\text{AEVL} = \text{Average Vehicle Length} + \text{Detector Length} \qquad \text{Equation 7.1}$$

This time interval indicates that although the AEVL calculated value exceeds the upper limit the sensor data appears to be consistent with the groundtruthing. The determination is consistent with previous research that indicates that anomalies in AEVL are possible given differing combinations of vehicles (5).

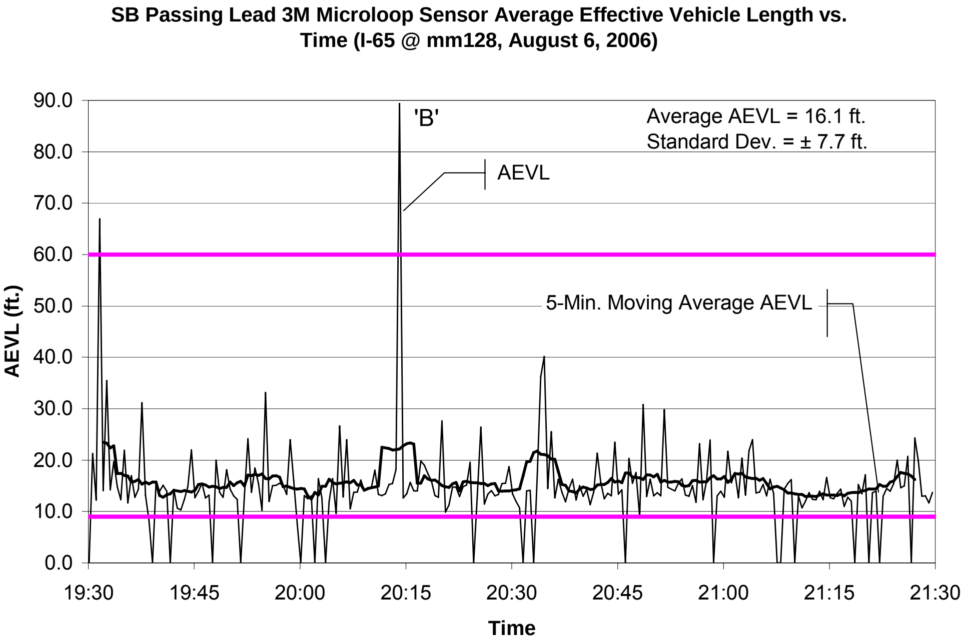
7.1.2.2. SB Passing Lane

The Microloop AEVL plots for the SB Passing Lane are shown in Figure 7.4. The most obvious instance where the AEVL calculated value exceeds the upper limit is Point ‘B’ in Figure 7.4. The interval values reported by the sensors and resulting calculated AEVL values are shown in Table 7.2

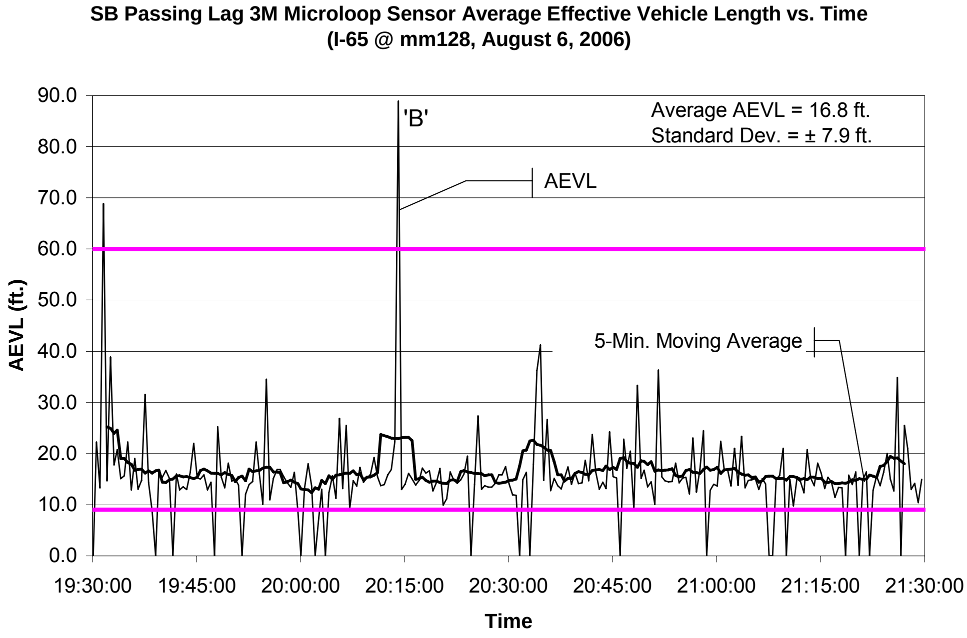
Table 7.2 Interval Values and AEVL for Interval ending at 20:14:05 (SB Passing Lane)

Sensor	**Volume (vehicles/interval)**	**Occupancy (decimal)**	**Speed (mph)**	**Calculated/ Estimated AEVL**
Microloop Lead	2	0.060	67.4	89.4 feet
Microloop Lag	2	0.060	67.4	88.9 feet
Groundtruth	5	N/A	N/A	N/A

The analysis of the video showed that the interval volume was actually 5 vehicles as opposed to the 2 vehicles reported by the Microloop sensors. The resulting effect on the AEVL is apparent, since the volume is in denominator of the AEVL equation (Equation 3.3) and a reduction of interval volume leads to an increase in the AEVL calculated value. This interval shows the effect of interval volume errors, and that the AEVL test can detect such errors.



a) SB Passing Lane Lead Microloop Sensor



b) SB Passing Lane Lag Microloop Sensor

Figure 7.4 Microloop AEVL vs. Time Plots SB Passing Lane of I-65 @mm 128

7.1.2.3. NB Passing Lane

The Wavetronix AEVL plot for the NB Passing Lane is shown in Figure 7.5. Point 'C' in Figure 7.5 clearly exceeds the upper limit AEVL value and was analyzed further. The resulting interval values are shown in Table 7.3.

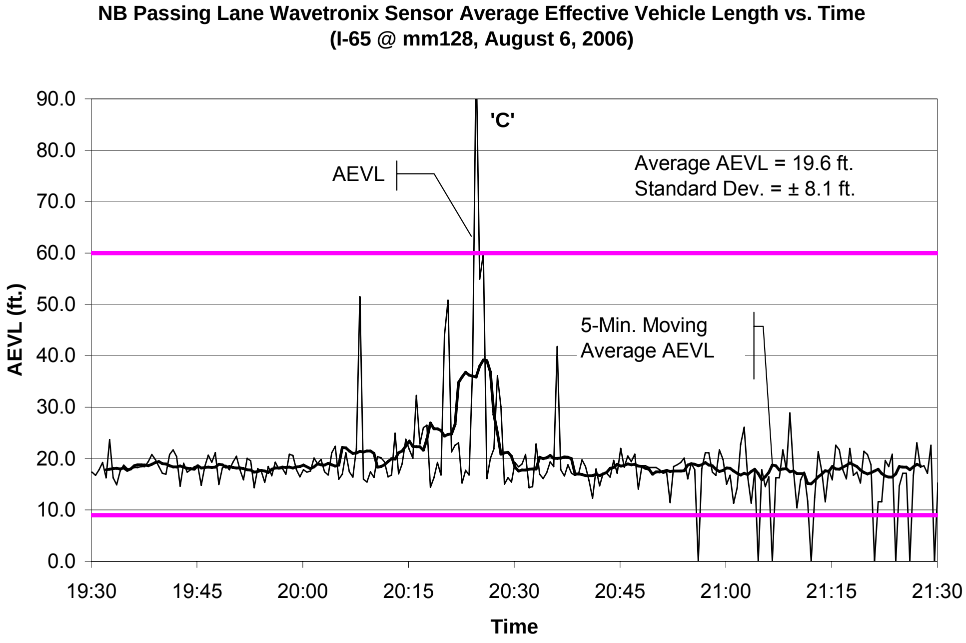


Figure 7.5 Wavetronix AEVL vs. Time Plot for NB Passing Lane of I-65 @mm 128

Table 7.3 Interval Values and AEVL for Interval ending at 20:24:35 (NB Passing Lane)

Sensor	Volume (vehicles/interval)	Occupancy (decimal)	Speed (mph)	Calculated/ Estimated AEVL
Wavetronix	6	0.61	22	98.4 feet
Groundtruth	7	N/A	7 (est.)	N/A

Based on the interval values it is clear that the overestimation of vehicle speed during this interval combined with the slight undercounting of interval volume caused the AEVL value to exceed the upper limit. In this instance the AEVL value clearly indicates that the data for this interval is suspect.

7.1.2.4. NB Driving Lane

The Wavetronix AEVL plot for the NB Driving Lane is shown in Figure 7.6.

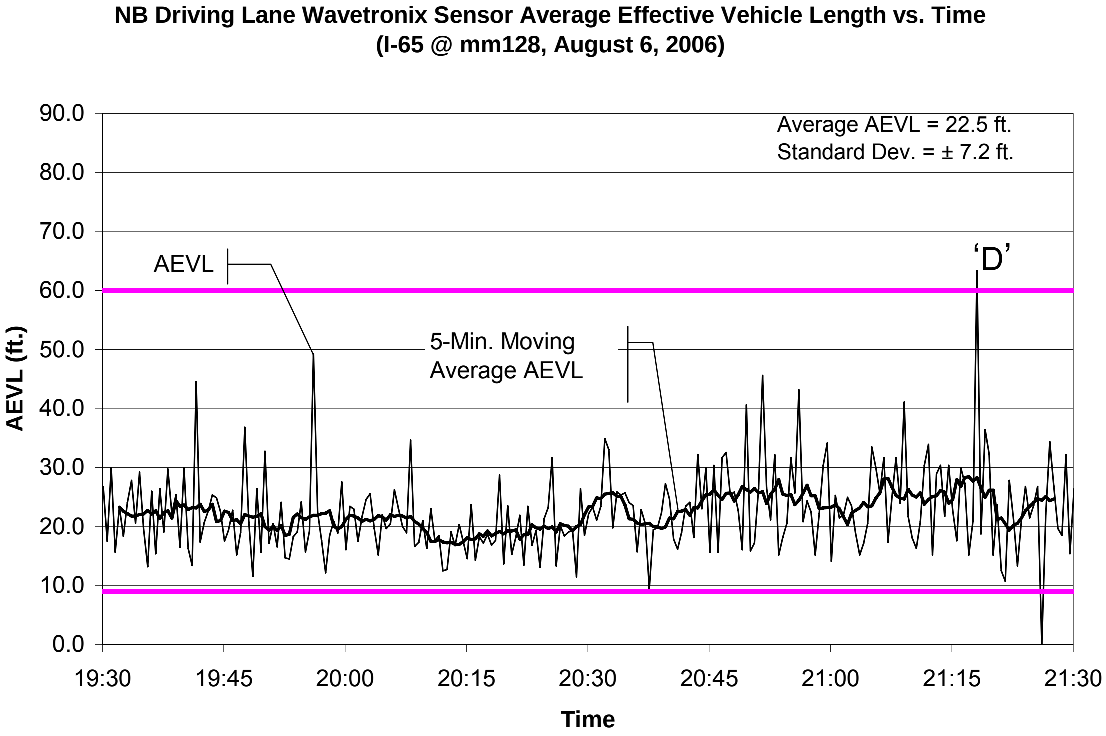


Figure 7.6 Wavetronix AEVL vs. Time Plot for NB Driving Lane of I-65 @mm 128

Point 'D' in Figure 7.6 is slightly outside the upper limit of the AEVL test, and was examined due to the fact that this is the only point that exceeds the upper limit for on the plot. The resulting interval values are shown in Table 7.4.

Table 7.4 Interval Values and AEVL for Interval ending at 20:18:05 (NB Driving Lane)

Sensor	Volume (vehicles/interval)	Occupancy (decimal)	Speed (mph)	Calculated/ Estimated AEVL
Wavetronix	4	0.09	64	63.4 feet
Groundtruth	13	N/A	30 (est.)	N/A

Analysis of the data for the interval ending at 20:18:05 for the NB Driving Lane indicates that the speed reported by the Wavetronix Smartsensor exceeded the estimated speed by a factor of roughly two. The speed overestimation by itself would tend to increase the AEVL value; however the undercounting of the interval volume by a factor of three tended to counteract the effect and led to an AEVL value slightly exceeding the upper limit. This interval for the Wavetronix Smartsensor indicates that it is possible for the sensor outputs to have errors that in effect cancel each other and provide a passing AEVL test value.

7.1.3. Summary

The intervals studied in detail in this chapter indicate that using the AEVL test for data quality screening can be very useful. Based on the cases examined for varying traffic conditions the intervals in which the AEVL values exceeded the upper limit were in fact suspect. In only one instance was the AEVL truly in excess of the upper limit and the sensors were reporting accurate values. This suggests the AEVL test can be used as a tool for assessing sensor data quality, with the knowledge that the test is not always perfect.

CHAPTER 8. FACTORS IMPACTING DATA QUALITY

8.1. DMAIC Step Four

The fourth step in the DMAIC performance improvement process is to improve the process. DMAIC step four is shown in Figure 8.1. The key to improvement is to apply the lessons learned from the previous step of root cause analysis and prevent errors from the same root cause. This chapter will discuss the factors that can affect data quality and proposes solutions to minimize them in the future, with the knowledge that even perfectly installed and calibrated sensors will not provide perfect data.

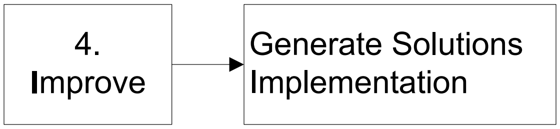


Figure 8.1 DMAIC Process – **I**mprove Step

8.2. Field Investigation of Freeway Traffic Sensors

One of the objectives of the project was to perform a field investigation and characterization of the factors which directly affect the quality of data from 3M Microloop Sensors. The ITS sensors evaluated is this project were 3M Microloop Model 702 sensors, which are located under the travel lane inside a pre-positioned conduit. The conduit can be placed under the roadway either by directional boring or by traditional open cutting techniques. The directional boring option is less disruptive, as it enables the roadway traffic to be maintained with minimal disruption.

8.2.1. 3M Microloop Construction Quality Control

Microloop sensor installation is inherently more complicated than the sidefire radar type sensor due to the additional factors involved with infrastructure installation and sensor placement. Factors that can affect the data quality include:

- Conduit Depth
- Conduit Horizontal Separation
- Splicing Quality
- Sensor Alignment Within Lane
- Construction Quality

8.2.1.1. Conduit Depth

The depth of Microloop conduit should be within the manufacturer’s tolerance of 18 to 24 inches from the top of the pavement to the center of the conduit. Conduit depth placement is critical in achieving optimal sensor performance. Placing the conduit too close to the pavement surface can compromise the pavement integrity, whereas placing the conduit too deep compromises sensor resolution for both volume and speed.

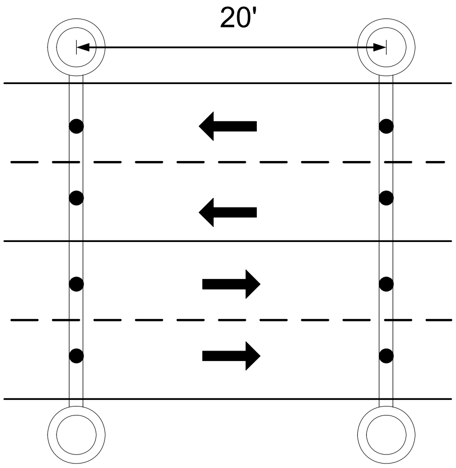


Figure 8.2 3M Microloop Typical Sensor Layout

Conduit depth in excess of the manufacturer’s tolerance is a maintenance issue as well, since the depth of the carrier entrance in the handhole has an effect on the ability of maintenance personnel to access the sensor carriers. This is clearly shown in Figure 8.3, as the technician is required to assume an uncomfortable position to remove and install the Microloop carriers. This leads to an increase in the time required to remove and install the sensors. The proper placement of sensors can significantly reduce the amount of time required to remove and install the sensors. The proper depth of conduit to allow easy access is shown in Figure 8.4 The depth of conduit placement is an aspect of the construction procedure that requires documentation at the time of placement. Directional boring machines have the capability to track the boring head, and drill depth can be determined while the conduit is being bored. This process involves the tracking of the conduit depth at 2’ intervals as specified in the 3M Installation Instructions (19). The documentation of conduit depth can be easily recorded in the field using , by tracking the depth at the center of the lanes during construction.

Figure 8.3 3M Microloop Sensors Placed Too Deep Below Pavement

Figure 8.4 3M Microloop Sensors Placed at correct depth for ease of maintenance access

8.2.1.2. Conduit Horizontal Separation

The distance between Microloop sensors is determined at the time the conduits are placed under the roadway. Proper documentation of the distance between conduits at the time of placement is easily documented by marking the distance between conduit locations during directional boring operations, or by measuring the distance between conduits during open trenching operations. offers a format for as-built documentation.

8.2.1.3. Sensor Alignment Within Lane

The sensor alignment within the lane is critical to sensor performance and the ability to correctly sense vehicles within the subject lane, and also minimizes cross lane detection. In general, the Microloop sensor is placed at the middle of the travel lane, with the exception being East-West roads which require the sensor location to be shifted to the north by one foot (19). Sensor placement, while appearing to be a trivial exercise can be difficult if the proper information is not known by the sensor installer. Lane widths and the offset distance from the handhole to the edge of the first lane are crucial distances that must be determined prior to sensor installation. Also assuming that lane widths are per plan or constant can lead to poor sensor performance and the need for additional field time for calibration and sensor repositioning. The lanes shown in Figure 8.5 were assumed to be 12’ wide and uniform when the Microloop sensors were initially installed. However due to poor sensor performance the sensor locations were reviewed. The excess width of the passing lane and the narrowness of the driving lane in Figure 8.5 led to sensor misplacement. Careful measurement of the lanes required working under flowing freeway traffic to achieve proper sensor placement and adequately performing sensors. Measurement of the lanes prior to sensor placement and approval of sensor placement by the technical service representative prior to sensor placement can greatly increase initial sensor placement success.

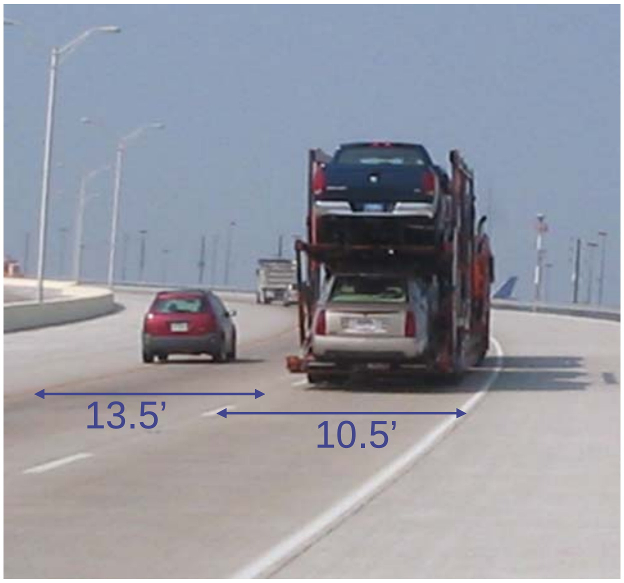


Figure 8.5 Constant lane width assumption proven false

8.2.1.4. As-Built Documentation

Proper documentation of as-built distances and physical criteria are essential to minimize the need for future time consuming measurements under heavy traffic conditions, or time consuming speed trap calibration using linear regression techniques (assuming the sensors are similarly calibrated for detection (18)). The required distances are shown in Figure 8.6, and a prepared form is shown in for Microloop sensor as-built documentation.

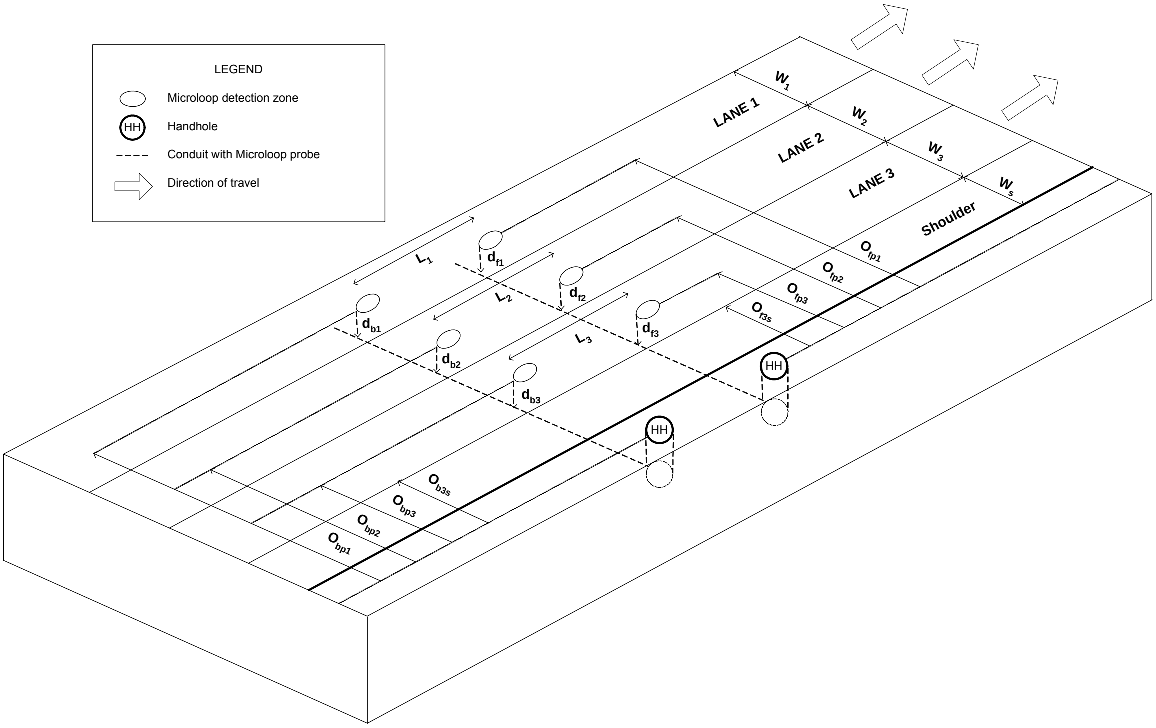


Figure 8.6 3M Microloop As-Built Sketch (5)

Table 8.1 3M Microloop As-Built Table (5)

Parameter Group	Symbol	Description	Typical Range	Manufacturer Tolerance	Actual Value
Width of lanes, shoulder and distance from edge of pavement to handhold	W_1	Lane 1 Width	11.5 - 12.5		
	W_2	Lane 2 Width	11.5 - 12.5		
	W_3	Lane 3 Width	11.5 - 12.5		
	W_s	Shoulder Width	11.5 - 12.5		
Spacing between probes	L_1	Lane 1 lead-lag spacing			
	L_2	Lane 2 lead-lag spacing			
	L_3	Lane 3 lead-lag spacing			
Depth measured from pavement surface to top of conduit	d_{b1}	Depth at back probe 1			
	d_{b2}	Depth at back probe 2			
	d_{b3}	Depth at back probe 3			
	d_{f1}	Depth at front probe 1			
	d_{f2}	Depth at front probe 2			
	d_{f3}	Depth at front probe 3			
Offset measured from edge of conduit in handhold to probe (see Figure 8.7)	O_{bp1}	Offset to back probe 1			
	O_{bp2}	Offset to back probe 2			
	O_{bp3}	Offset to back probe 3			
	O_{b3s}	Offset to back shoulder			
	O_{fp1}	Offset to front probe 1			
	O_{fp2}	Offset to front probe 2			
	O_{fp3}	Offset to front probe 3			
	O_{f3s}	Offset to front shoulder			
Describe any subsurface infrastructure (conduits, drains, pipes, utilities, culverts) within 25' of any probe and note on as-built sketch					

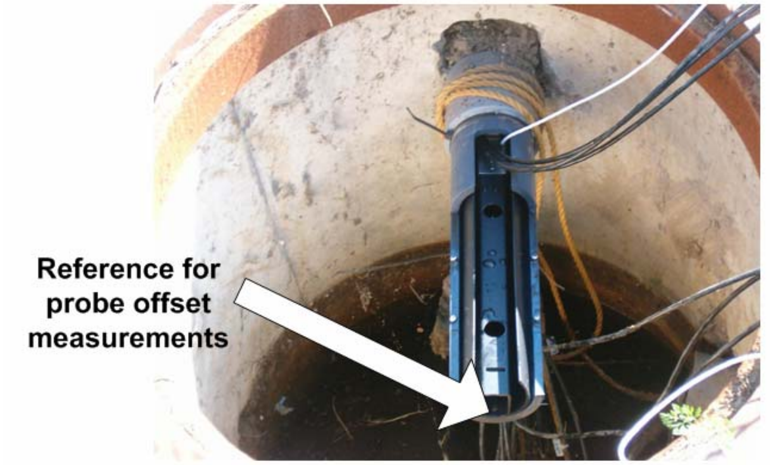


Figure 8.7 Edge of Conduit in Handhole (5)

CHAPTER 9. DOCUMENTATION, PROCESS MONITORING & POLICY CHANGES

9.1. Introduction

The final step of the DMAIC model is process control, as shown in Figure 9.1 Control is accomplished through documentation, process monitoring and changing policy. The documentation aspect of the final step is critical, from the construction phase through the life cycle of the sensor. The process monitoring of freeway traffic sensors should be continuously ongoing to provide the best possible data quality. Policy changes should be undertaken at appropriate times, as the need arises. This may involved the need to raise accuracy levels for site acceptance or revise contract payment procedures.

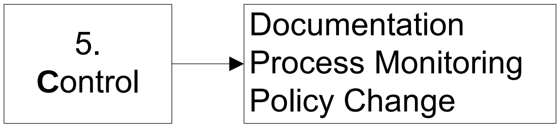


Figure 9.1: DMAIC Model – Control Step

9.2. Documentation

The documentation aspect includes taking notes during construction processes, to ensure that the construction specifications are met. Documentation should also be provided by the contractor for all calibration prior to acceptance of the ITS site by the Transportation Agency. This documentation would cover the physical as well as non-physical properties of the sites, such as: configuration files, sensor sensitivity settings, calibration factors for speed and occupancy, and all other setup parameters.

Documentation also needs to be mandated after construction acceptance and during the ongoing process monitoring phase. Sensor problems, repair and recalibration should be logged for further analysis and to determine and account for any possible trends in future data due to maintenance activities. Use of a database for documentation can easily provide access to all sensors maintenance and calibration activities. Such a database can also be useful in performing sensor life cycle cost analysis.

9.3. Process Monitoring

On-going sensor monitoring is necessary to ensure that the data provided to the Traffic Management Centers is of high quality. The use of Statistical Process Control, which has previously been applied to Weight In Motion (WIM) sensors, is a useful approach that can improve sensor data quality (6). Use of a procedure to identify suspect sensor data is suggested in Figure 9.2.

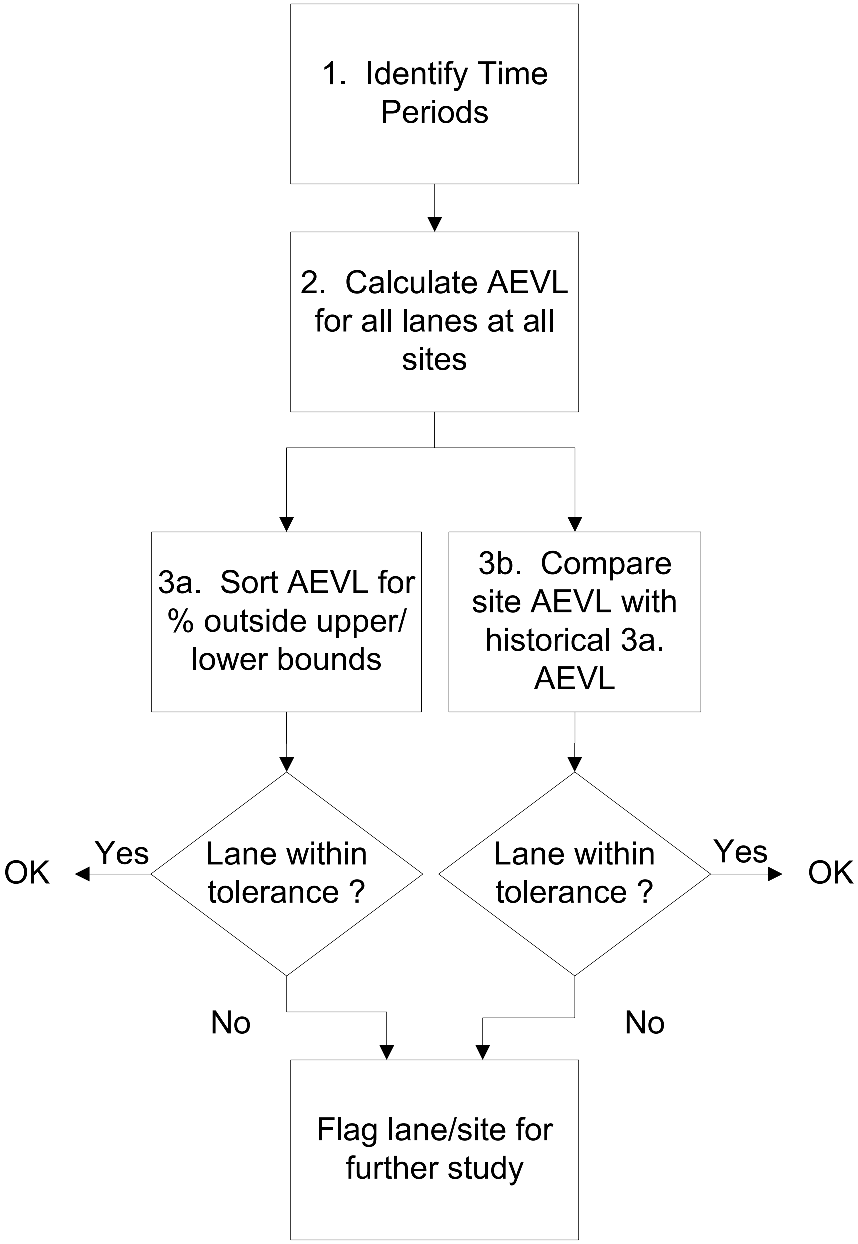


Figure 9.2 Process Monitoring Procedure for ITS Sensors

The monitoring process using SPC is based on the desire to determine when random changes in the process have occurred and taking action to correct the problem. The average and standard deviation of a process, in this case the AEVL values from freeway traffic sensors, will be used to establish control limits for error detection. Establishing the control limits of the process relies on the assumption that the values under control are normally distributed. The assumption of a normally distributed set of values provides the knowledge that over 95% of the data will lie within two standard deviations from the overall average value, as shown in Figure 9.3.

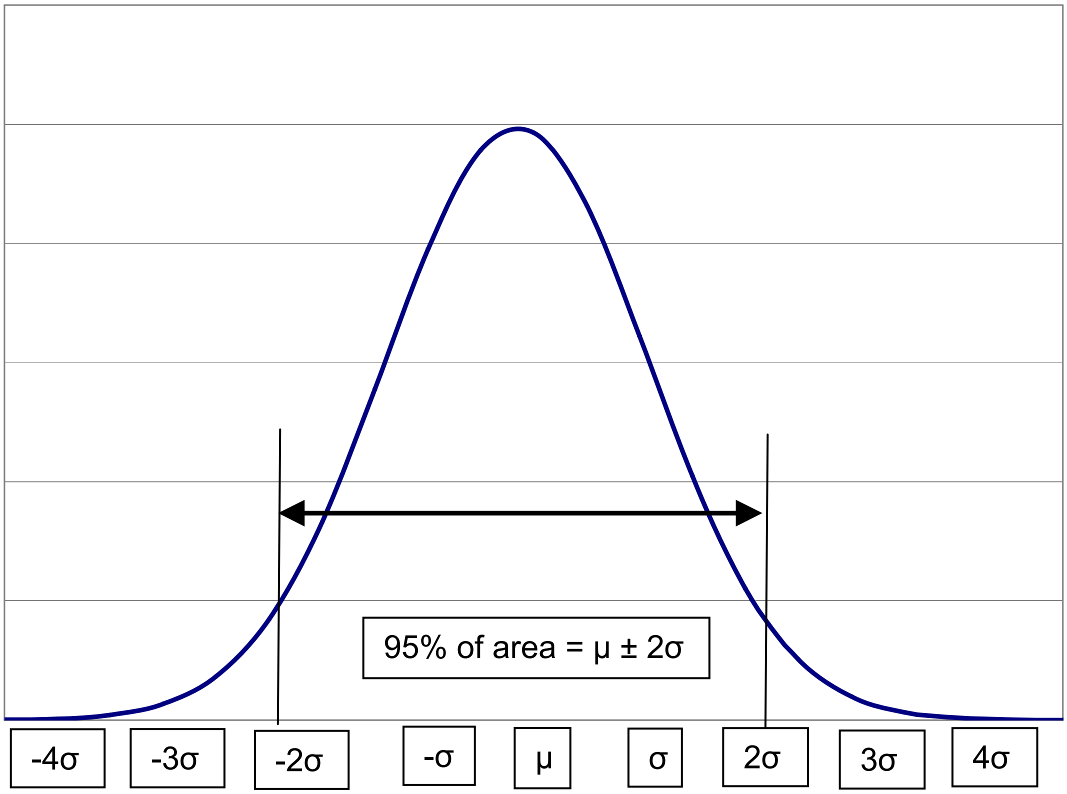


Figure 9.3 Area Under Normal Distribution Curve

For control chart purposes limits are established that are predicted to contain the previously mentioned 95% of AEVL values. However, unlike a production process the variability of traffic flows may differ due to unknown parameters, such as weather conditions. Process monitoring can however significantly reduce the limits of acceptable AEVL test values, by using the SPC process. Lane specific values can be determined from historical data, and average values and standard deviations can be calculated from the data. Control limits can be established as shown below:

$$\text{Upper Control Limit} = \text{Average AEVL} + 2 * \text{Standard Deviation.} \qquad \text{Equation 9.1}$$

$$\text{Lower Control Limit} = \text{Average AEVL} - 2 * \text{Standard Deviation.} \qquad \text{Equation 9.2}$$

Use of the above described process for sensor data quality monitoring at the test location has produced the chart shown in Figure 9.4. This chart shows that the Average AEVL value for the SB Driving lane during test hour from 9:00AM to 10:00AM is fairly consistent for the Wavetronix and RTMS sensor; however there are several instances where the data appears to fall outside the control limits. This could be an indication that the limits are too narrow to account for the variability of traffic composition or that the sensor data is suspect.

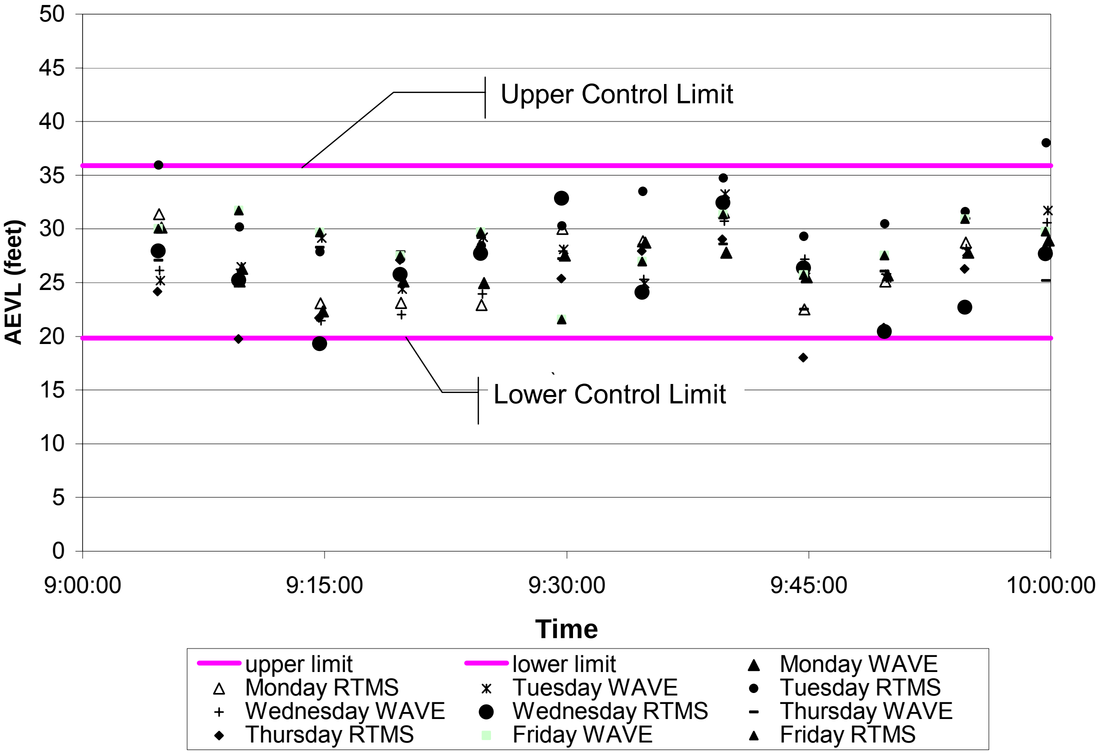


Figure 9.4 Example of Control Chart for SB Driving Lane @ I-65 mm 128 site

The same procedure was used to prepare a control chart for the SB Passing Lane. This chart is shown in Figure 9.5.

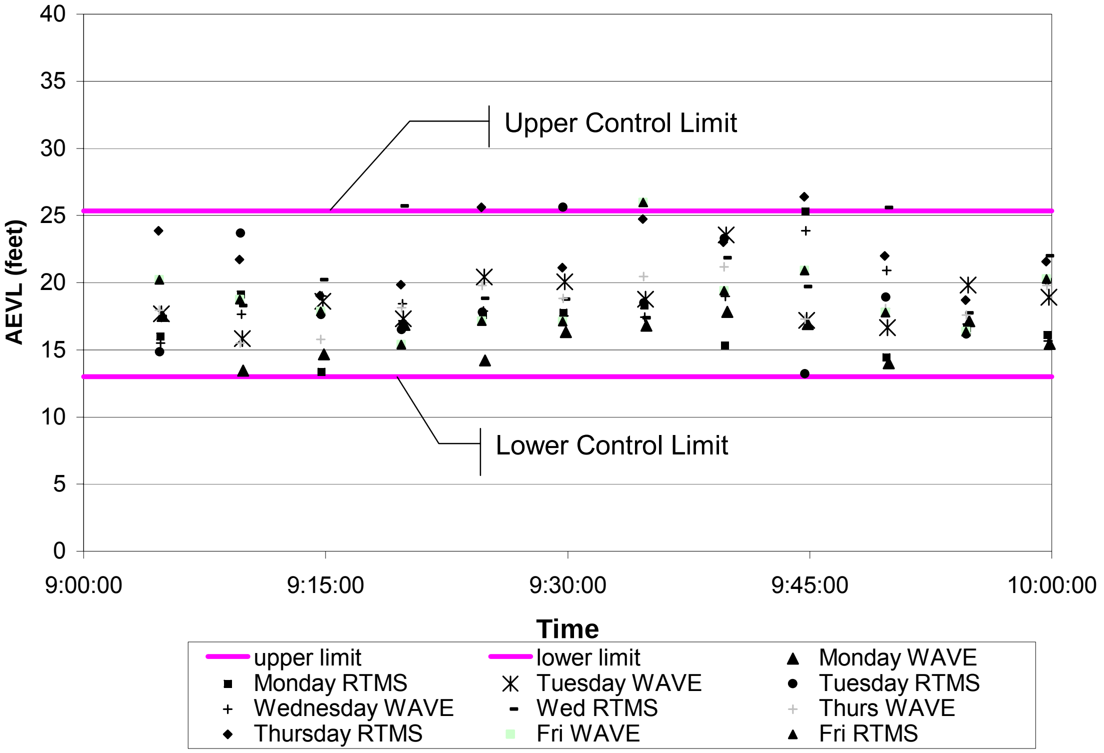


Figure 9.5 Example of Control Chart for SB Passing Lane @ I-65 mm 128 site

9.4. Policy Change

Policy changes should be implemented to continually improve sensor data quality. Examples of policy changes include updating construction, maintenance, and performance specifications to reflect new procedures, technology and solutions to minimize root error causes. The ideal situation for data quality monitoring would be to have co-located sensors in all locations. However, due to cost constraints the co-location of sensors could be utilized on an as needed basis as part of the on-going health monitoring assessment.

CHAPTER 10. CONCLUSION

This document has outlined the DMAIC performance improvement procedure and further applied the research performed earlier on freeway sensor performance metrics (5). The application of the DMAIC model has been shown to provide a solid framework for ongoing quality control monitoring that can improve the confidence with which INDOT uses freeway sensor data.

This document has outlined the DMAIC performance improvement procedure and further refined the research performed earlier on freeway sensor performance metrics (5). The application of the DMAIC procedure has been shown to provide a solid framework for ongoing quality control monitoring that can improve the confidence with which INDOT uses freeway sensor data.

The case studies of Average Effective Vehicle Length (AEVL) have shown that the combination freeway sensor outputs in the form of: speed, occupancy and volume into one function is an efficient and effective tool for finding suspect data records. The case study shown in Figure 7.4 clearly shows that the AEVL test is capable of determining problems with freeway sensor volume counts. The case study shown in Figure 7.5 indicates that the AEVL test is also effective at identifying problems with freeway sensor speed data. However, the AEVL test has also been found to be susceptible to errors when the interval volume is small and the vehicles themselves exceed 60 feet in length, such as in the case study illustrated in Figure 7.2 and Figure 7.3.

The next step is to work with INDOT developers to:

1. Produce AEVL values on a daily basis for selected hours at all stations (all lanes) and rank order them. AEVL values to be based on strategically selected time intervals.
2. Implement the triage system similar to that shown in Figure 9.2.
3. Establish reasonable AEVL control limits, perhaps based on Equation 9.1 and Equation 9.2.
4. Develop staff procedures for evaluating exceptions and prioritizing field investigations.
5. Develop a portable field trailer/van for verifying volume, occupancy and speed data at sites deemed out of calibration.

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