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16. Abstract

Performance measures play a critical role in the operation of Intelligent Transportation Systems (ITS), because they provide feedback to the operators regarding system operations and efficiency. Traffic management systems use archived data, provided by various sensors, as a basis for describing normal conditions and predicting traffic conditions that may be expected at a particular time and place in the highway system. However, data quality is one of the principal concerns of archived ITS data users for the following reasons: 1) Manual inspection techniques are unable to detect significant errors because of the large volume of ITS data; 2) Only minimal error detection can be performed as the data is being collected; 3) Sensors may only fail intermittently and not affect long-term averages; 4) Sensor failures may be masked by congestion or incidents.

This project examined several quality control issues on one of the nation's busiest sections of Interstate, the Borman expressway (I-80/94). Various tests such as speed and volume comparisons, data availability and average effective vehicle length test were developed and applied, revealing significant inconsistency in data quality provided by different detection technologies. Results that document these problems are presented in this study and causes of non-random changes are identified. Finally, several recommendations for improving construction and configuration procedures are proposed. Several simple performance metrics are also documented that transportation agencies can use to assess the quality of traffic data and sustain that quality over time.

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IMPLEMENTATION REPORT

This report has developed a quality control procedure that can be used by Indiana Department of Transportation to evaluate the performance of ITS sensors deployed to freeway arterials. Possible metrics that ensure preservation of data quality at a high level, for a long period of time are summarized as follows:

- Implement formalized procedure for vendors and contractors to provide as-built installation documentation.

- Apply quality control measurement immediately after sensor installation and at regular intervals to validate both the sensors and communicating infrastructure.

- Co-locate microloops and RTMS sensors to ensure that quality control tests can be run without massive manual data collection efforts.

- Report occupancy to one decimal to facilitate more robust average effective vehicle length estimation during periods of low volume.

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CHAPTER 1. INTRODUCTION

1.1. Introduction

The problem of traffic congestion on urban freeways has been steadily been worsening for decades. As a result of this phenomenon, delays for motorists have been dramatically increased, air and noise pollution problems have become worsened, while transportation safety always remains a significant challenge. In order to mitigate the negative effects of congestion, traffic management systems, responsible for monitoring and responding to traffic conditions, has been developed by transportation agencies.

Traffic management systems, particularly those that manage freeways, typically deploy sensors at various locations to collect several types of traffic data (volume of vehicles, speeds, occupancy, etc). Data collected by intelligent transportation systems (ITS) can then be processed to derive information about the performance of the transportation network.

Several detection technologies are used to monitor traffic conditions and collect traffic data: Inductive loop detectors, radar, acoustic and video imaging devices are potentially rich sources of data about transportation characteristics.

However, one of the primary concerns of ITS data users is how to assess the quality of the data, as only minimal error detection is performed as the data are being collected. Although detectors are usually tested immediately after installation, it is well known that they operate under very difficult conditions and are susceptible to degradation in accuracy or complete failure. Therefore, the development of data quality control procedures to screen erroneous data has become a critical issue.

1.2. Six Sigma Process

Quality control programs have been in place for many years, to improve various manufacturing procedures. One of the most popular approaches concerning quality control is Six Sigma, an implementation of quality principles for improving a company's performance by reducing the number of defective parts and customer complaints.

A structured methodology for executing Six Sigma project activities is the Define, Measure, Analyze, Improve and Control process, abbreviated DMAIC (1, 2, 3). Many of the preliminary theory and discovery steps of this model have been addressed in this project. Figure 1-1 illustrates the steps of the DMAIC performance improvement model, which can be applied by any transportation agency to improve quality control of their traffic network data (4).

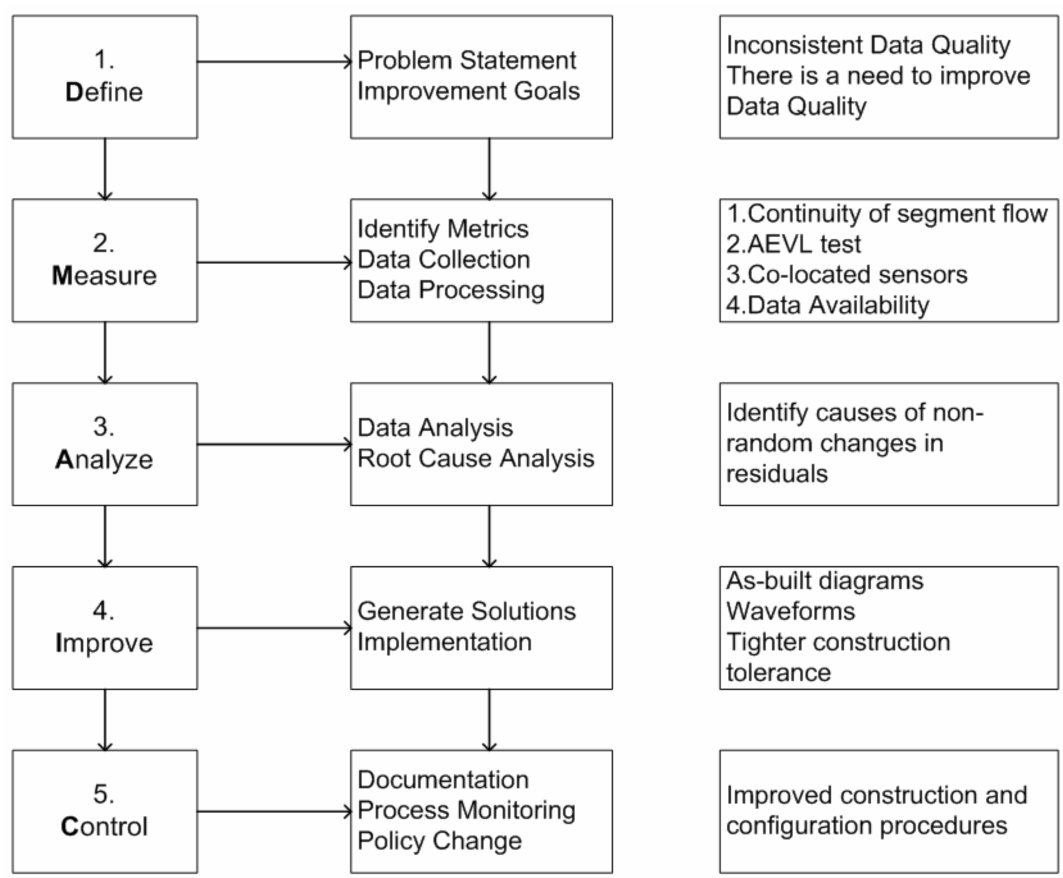


Figure 1-1: DMAIC Performance Improvement Model

1.2.1. Define

The first step in DMAIC is to define the problem statement and goals for improvement. The problem that is being addressed in this project is the quality of data provided by freeway traffic sensors. Accurate data is required by many Traffic Management Center (TMC) applications, but is currently very difficult to achieve. The goal of this project is to develop procedures to ensure high quality data is provided to all ITS data users. Detailed aspects concerning the Define step are covered in Chapter 2.

1.2.2. Measure

The second step in DMAIC is to identify metrics for assessing data quality, collect the data, and process the data. This can be done by identifying valid metrics that will help achieving the defined goals. The metrics identified in this project are the following:

- Continuity of segment flow between sensors seven hundred feet apart
- Reasonable Average Effective Vehicle Length (AEVL) test
- Continuity of flow at co-located sensors
- Data availability test

The details of the Measure step are extensively covered in Chapters 3, 4, 5 and 6.

1.2.3. Analyze

The third step in DMAIC is to analyze the data and determine the root cause of data trends. As data quality improves, the data will be more useful and previously undetectable trends will become more evident. It is very difficult to determine what causes sensors to fail. Chapters 5, 6 and 7 present data analysis that applies the defined metrics and identifies causes of non-random changes in residuals.

1.2.4. Improve

The fourth step in DMAIC is to improve the system by generating possible solutions and selecting the best for implementation. Once the factors affecting the ITS data are identified in the Analyze step, solutions are generated to minimize or eliminate the influence of these factors. Several proposed solutions are discussed more analytically in Chapter 8, including:

- As-built diagrams of sensor stations
- As-built waveforms obtained from sensors
- Tighter construction tolerance for sensor installations

1.2.5. Control

The fifth and final step in DMAIC is to monitor the processes, document process changes, and implement new policies to maintain a high level of quality. Although it is up to the system operator to record sensors maintenance or replacement, it is very important that all calibration and maintenance activity performed on the sensors be documented. Several improved construction and configuration procedures are discussed in more detail in Chapter 8.

1.3. Summary

The following chapters introduce detection technology (Chapter 2), summarize past efforts at quality control (Chapter 3), develop the DMAIC quality control measurements (Chapter 4), develop the DMAIC analysis (Chapter 5 and 6), apply the DMAIC quality control procedures to the Borman data set (Chapter 7), and finally propose improvements for constructing future traffic data collection infrastructure (Chapter 8).

CHAPTER 2. DETECTION TECHNOLOGIES

2.1. Introduction

Automated monitoring of traffic conditions is one of the most crucial functions of a traffic management system. Various detection technologies have been used for the last three decades, including inductive loop detectors, radar, acoustic and video imaging devices. However, the data quality that these sensors provide to the data analysts and system's operators remains a significant concern.

This project focuses on freeway detection technologies that were deployed on the Borman Expressway (I-80/94). From 2000 - 2004, seventy-five sensors including inductive microloops and RTMS (Remote Traffic Microwave Sensor) were deployed at several sections of the interstate. This chapter documents the detection technologies used along that corridor.

2.2. Microloops

The non-invasive microloop detection technology has been used in advanced detection applications to replace the "traditional" 6x6-loop detection technology. Several advertised advantages of the microloop detection technology are (4, 5):

- Low loop maintenance and pavement repair costs
- Installation efficiency; traffic lanes are not closed for long periods of time
- Installation simplicity; probes are fit in specially designed carriers
- Flexibility; easily reposition or readjust probe placement to improve vehicle sensing accuracy

2.2.1. Components

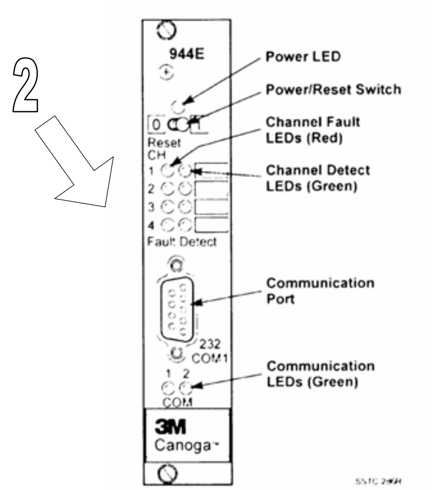
The 3-M Canoga microloop vehicle detection system consists of the following components (6):

1. Non-invasive microloop probes
2. Canoga traffic monitoring cards

3. Installation kit and carriers
4. Home-run cables required to install the non-invasive microloop

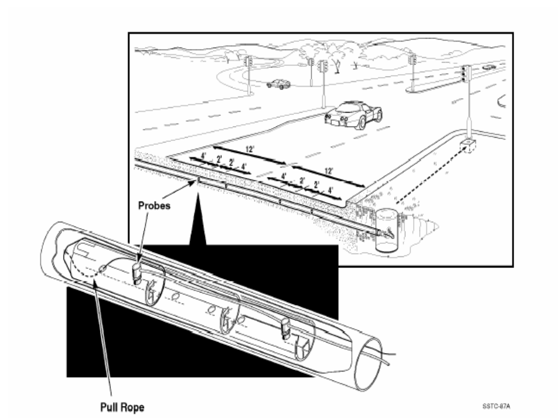
Figure 2-1 shows the main components of the microloop vehicle detection system.

a) Model 702 non-invasive microloop probe



b) Front panel of Canoga 944E Traffic Monitoring card

c) Model 702 installation kit and carriers



d) Model 702 non-invasive microloop probes installation

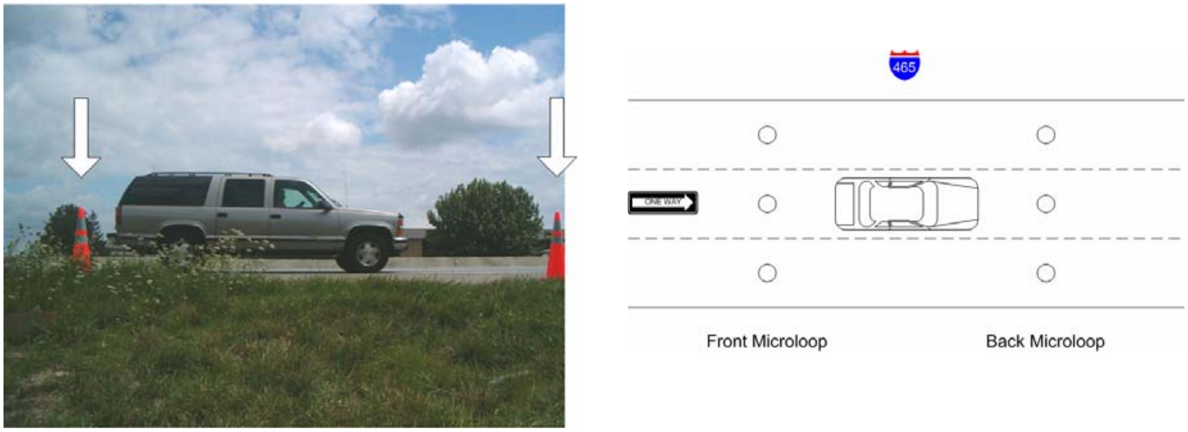
Figure 2-1: Model 702 non-invasive microloop probes installation

2.2.2. Description - Basic Settings

The non-invasive microloop probe is a small cylindrical passive transducer that transforms changes in the vertical component of the earth's magnetic field to changes in inductance. Vehicles containing vertical component of ferromagnetic material "focus" the earth's field, increasing the magnetic field at the sensor when the vehicle moves over the sensor. Inductance changes can be sensed by suitably configured Canoga vehicle detectors. A typical inductance change caused by an auto in a microloop probe set is 450 nanohenries per probe in the probe set and the typical sensitivity that would be used on a channel connected to a microloop probe set is 4 (6). However, the response of a microloop probe set to a vehicle is significantly affected by the depth of the probes from the road surface, by the angle of the probe with respect to being vertical and occasionally by reinforcing steel or drainage structure in the road. The recommended installation of the conduit with the carriers and the probes is 18-24 inches below the road surface, using horizontal directional drilling or open trenching techniques. Additionally, another setting that can affect microloop system's operation is bridge time, which is the time from the end of the last call during which a new call will be considered as being caused by the same vehicle. Bridge time is used to prevent most class 9 vehicles from being double counted. Example of a class 9 vehicle is shown in Figure 2-2. With bridge time set to 0.40 seconds, most class 9 vehicles traveling at speeds greater than or equal to 56 km/h (35 mph) will be counted as a single vehicle.

Figure 2-2: Class 9 vehicle

Figure 2-3 depicts an example of a detection zone defined by microloops on a test site located on I-465 (Indianapolis).



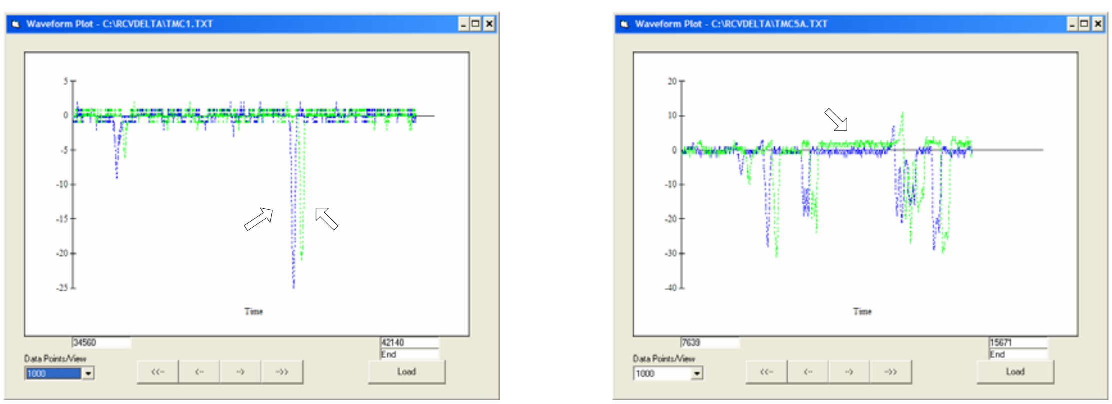
a) Microloop detection zone

b) Plan View

Figure 2-3: Microloop detection zone at I-465 test site

2.2.3. Waveforms

A procedure frequently used to document the performance of the microloops is the waveform test (7). This test can be operated by using a vendor-supplied program (Rcvdelta.exe) to check channels noise levels by gathering and plotting simple waveform graphs. Figure 2-4a illustrates an example of a waveform graph indicating acceptable noise levels but noticeable amplitude differences between the lead waveform represented with the blue line and the lag waveform represented with the green line.



a) Differences between lead-lag probes

b) Noise Problems

Figure 2-4: Example of waveform graphs

After starting the waveform documentation procedure, data is transmitted continuously for two channels at the same time, and every measurement sample is taken by the traffic monitoring card, so that the signal can be analyzed externally. For instance, the values of the data can be used to compute an estimate of maximum inductance change (Delta L) in nanohenries for a recently detected vehicle, or to reveal a non-tolerable channel noise level that will increase measurement errors as shown in Figure 2-4b. If the waveform graphs indicate that there is no noise, and the lead waveform has the same shape and magnitude as lag waveform, then we accept that the data reported by the two channels are reasonable.

2.2.4. Operating modes - Data collection

Traffic monitoring cards have two vehicle detection modes; Presence mode and Pulse mode. These modes are independently for each channel. In Presence mode the detect output detection corresponds to the period of vehicle presence over the detection zone. On the other hand, selecting Pulse mode causes each vehicle, at the time it is detected, to produce a switch/call output pulse with ON time of pulse (approximately 118 milliseconds). For the traffic monitoring cards on the Borman expressway, Presence mode is selected in order to record the following type of data:

- Vehicle Counts
- Occupancy
- Speed (Using channel pair configuration)

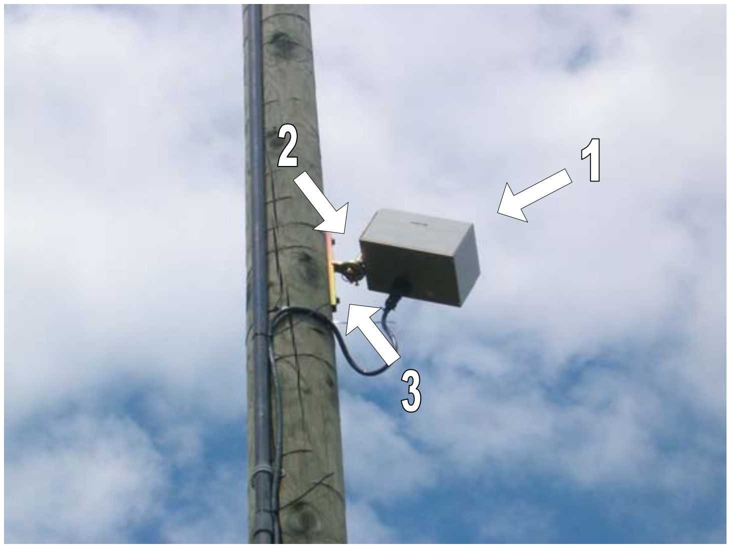
2.3. Radar Traffic Microwave Sensor (RTMS)

The RTMS is a device specially designed for traffic sensing applications. Installing a single device that can cover up to eight lanes of traffic, at the side of the road, avoids the disruption of lane closures and has potential economic benefits.

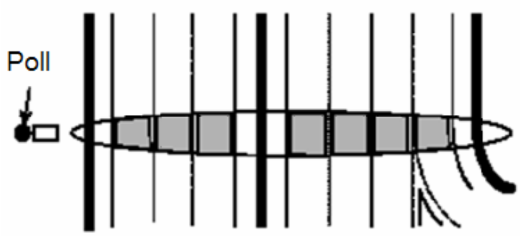
2.3.1. Components

The main components of the RTMS system are shown in Figure 2-5:

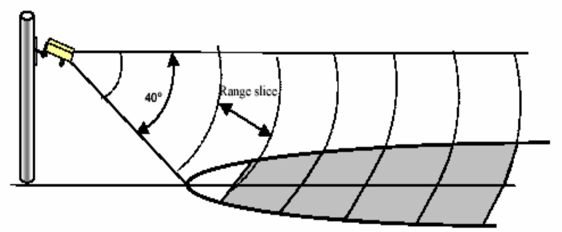
1. RTMS sensor
2. Ball joint mounting bracket
3. Connector kit



a) Radar Traffic Microwave Sensor (RTMS)



b) Side-fired configuration



c) Range slice of RTMS

Figure 2-5: RTMS Sensor at I-465 test site

2.3.2. Description - Basic Settings

The RTMS sensor (8) measures the distance to objects in the path of its microwave beam, which is approximately 40 degrees in height and 15 degrees wide, with a range of 60 meters (approximately 200 feet). The ranging capability allows the RTMS to detect stationary and moving vehicles in multiple detection zones as shown in Figure 2-5c.

The RTMS has two mounting configurations; side-fired configuration, which is used on the Borman expressway, and forward-looking configuration. In the side-fired configuration, the RTMS is mounted on a roadside pole with its footprint aimed at right angle to the traffic lanes as shown in Figure 2-5b. Range-slices corresponding to the location of traffic lanes are defined as detection zones. Each detection zone may consist of one or more range-slices and its length is determined by the width of the beam's footprint.

The sensor receives reflected signals from all surfaces within its beam so it maintains a background signal level from fixed objects in each range slice. Vehicles are detected when their reflected signal exceeds the background level of their range slice by a certain amount called "Threshold".

The level of the received signal from vehicles varies depending on the shape of the vehicle and can fall below the threshold during brief intervals called nulls. In order to prevent multiple counting due to these nulls, the RTMS signal processing includes an Extension Delay Time to bridge the nulls and hold presence indication. The threshold level and the Extension Delay Time are set to default values when the mode of operation is selected.

2.3.3. Operating Outputs - Data Collection

The detection of a vehicle in any zone is registered in two independently operating outputs:

- Zone Contacts: Contact pairs corresponding to the detection zone can be connected to traffic controller for traffic measurements, for as long as the detection persists.
- Serial Port: RTMS internal firmware uses vehicle detection to accumulate volume, occupancy, average speed and classification by length over a defined period. At the end of the period the accumulated data, containing measurements for all zones is transmitted over the serial port.

2.4. Discussion

This chapter summarizes the detection technologies used in this study. The following chapters will summarize evaluations of detection technologies. Subsequent chapters will build upon evaluation techniques proposed by other researchers and incorporate them into a DMAIC model, introduced in Chapter 1.

CHAPTER 3. LITERATURE REVIEW

3.1. Introduction

Performance measures play a critical role in the operation of Intelligent Transportation Systems (ITS), because they provide feedback to the operators regarding system performance.
Traffic management systems use archived data, provided by various sensors, as a basis for describing normal conditions and predicting traffic conditions that may be expected at a particular time and place in the highway system. However, data quality is one of the principal concerns of ITS data users for the following reasons:

1. Manual inspection techniques are unable to detect significant errors because of the large volume of ITS data.
2. Only minimal error detection can be performed as the data is being collected.
3. Sensors may only fail intermittently and not affect long-term averages.
4. Sensor failures may be masked by congestions or incidents.

Various sources contribute to inaccuracies in traffic ITS data. For instance, the type of sensor (inductive loops, radar, acoustic and video imaging devices), improper installation, infrequent calibration, infrequent maintenance, communication system problems and monitoring software can all contribute to data quality problems.
Resent research focuses on data screening techniques by defining reasonable quality levels for data accuracy and availability and on product evaluations by comparing the performance of loop detectors with microwave vehicle detection systems. Fekpe, 2003 proposed the following quality control measures in order to evaluate the reliability of the data provided by the detectors (9):

- Accuracy
- Availability or Completeness
- Validity
- Timeliness
- Coverage
- Accessibility or Usability

Several of these data quality measures can be used for evaluating the ITS monitoring data (e.g. speed, volume, occupancy) collected by inductance loop detectors and the Remote Traffic Microwave Sensor (RTMS) on I-80/94 (Borman expressway) in northwest Indiana.

3.2. Accuracy

Accuracy is always a concern for ITS data users because all traffic sensors are subject to some errors. For example, loop detectors in adjacent lanes could both count a vehicle in the process of changing lanes, resulting in double counting the vehicle.

A white paper published by the Federal Highway Administration (10) defines accuracy as the degree of agreement between a data value or a set of values and a source assumed to be correct. Therefore, accuracy can be a measure of the traffic monitoring equipment's ability to represent the actual traffic conditions.

Furthermore, ITS America guidelines (11) define quality levels of “good”, “better” and “best” providing specific level criteria for each attribute. For instance, ten to fifteen percent error in travel times and speeds is classified as a “good” level of accuracy, five to ten percent error as a “better” level and less than five percent error as the “best” level of accuracy (Table 3-1).

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

Table 3-1: Guidelines for Traffic Sensor Data Quality Levels (11).

In another white paper about data quality measures, Tarnoff suggests that speed and volume accuracy levels, together with requirements concerning timeliness and availability differ depending on the data users (12). Although Tarnoff presents these criteria as a “starting point for the discussion of these issues”, he demonstrates the importance of considering local and national implementations separately.

Possible performance requirements according to Tarnoff’s suggestions are illustrated in Table 3-2:

Measure	**Application**	**Requirement**	
		Local Implementation	**National Implementation**
Speed Accuracy	Traffic Management	5-10 %	5-10 %
	Traveler Information	20 %	20 %
Volume Accuracy	Traffic Management	10 %	n/a
	Traveler Information	n/a	n/a
Timeliness	All	Delay < 1 minute	Delay < 5 minutes
Availability	All	99.9 %	99 %

Table 3-2: Possible Performance Requirements (12)

An acceptable level of accuracy can be achieved when the reported vehicle counts are close to the actual number of vehicles, or perhaps when the reported speeds are similar when provided by two different types of sensors (e.g. microloops and RTMS).

The Detector Evaluation and Test Team of Caltrans documented that Microwave Vehicle Detection System (MVDS) technology, when properly installed and calibrated, can deliver better than 95% overall vehicle count accuracy at 5-min and 30-sec intervals and 95% average speed accuracy at five minute intervals. However, they also stated that MVDS was found not to be suitable for accurately measuring occupancy (13). In addition, Caltrans established acceptable levels of errors (95%) concerning speed, volume and occupancy as depicted in Table 3-3.

Data	Units	Accuracy	Primary Use
Volume	Number of vehicles per hour	95% per 30 sec interval/lane	Traffic studies and census; performance measurement; Local-responsive ramp metering; corridor-wide incident detection and ramp metering; traffic responsive signals, mainline speed estimation (where necessary)
Speed	Miles per hour	95% per 30 sec interval/lane	Ramp metering, performance measurement, traveler information, incident management
Occupancy	Percentage of time of vehicle presence	95%	Local-responsive ramp metering; corridor-wide incident detection and ramp metering; traffic responsive signals, mainline speed estimation (where necessary)

Table 3-3: Caltrans acceptable levels of errors for volume, speed and occupancy

Moreover, Turochy developed a procedure for detector data screening in traffic management systems based on the tests shown in Table 3-4 (14):

Tests	Data-screening Procedure
Maximum occupancy threshold	If the occupancy value for a particular station and time period is higher than that considered feasible for traffic, then the particular record is considered erroneous. The threshold occupancy value for an individual record was set to 95%.
Overall maximum volume threshold	For traffic data collected at 20-second intervals, a maximum volume threshold of 17 vehicles per lane was set.
Positive volume with zero speed	Such a combination is infeasible.
Maximum volume threshold with reported occupancy zero	This test ensures that when occupancy is reported as zero, the corresponding volume is not so high as to be considered infeasible (e.g. early morning hours).
Average Effective Vehicle Length (AEVL) test	AEVL is a function of occupancy, volume and speed data for individual records and can be calculated from the data by using traffic flow theory principles. If the data falls within the threshold values, they are considered acceptable.

Table 3-4: Proposed data-screening procedure (14)

3.3. Data Availability

Another important attribute of ITS traffic monitoring data is availability or completeness because of the continuous operation of the collection equipments. Turner defines data availability as the degree to which data values are present in the attributes that require them (e.g., volume and speed are attributes of traffic) (10). Data completeness is typically described in terms of percentages or number of data values.

The characteristics of missing data may vary considerably, depending on the type of monitoring equipment, field controllers and traffic management software. Typical causes of missing data, as well as how the causes affect missing data are depicted in Table 3-5 (15).

Cause of Missing Data	Characteristics of Missing Data	
	Spatial Attributes	Temporal Attributes
Construction activity that disrupts the traffic monitoring installation	Data missing at a single location or several consecutive locations along a corridor	Data typically missing for extended periods of time (i.e. several months, but depends upon type of construction activity)
Failure of traffic monitoring equipment (could include the inductance loop hardware or the field controller software)	Data missing at a single or several isolated locations	Data missing for short or long periods of time (i.e. several minutes to several weeks)
Disruption of communications between field controllers and central traffic management system	Data missing at a single or several isolated locations	Data typically missing for short periods of time (i.e. less than several minutes)
Failure of central traffic management system or data archiving system (hardware or software)	Data missing at all locations (or all locations on a given computer server)	Data typically missing for short periods of time (i.e. several hours to less than one day)

Table 3-5: Typical Causes and Characteristics of Missing ITS Traffic Monitoring Data (15).

Awareness of missing data characteristics can be critical in order to select the most appropriate way to manage missing data in aggregation, summarization and analysis of the results. In addition, it is important for the data users to be informed about missing data when analysis results are presented.

3.4. Coverage

An additional proposed data quality measure is the coverage of the studied area. Coverage can be defined as the degree to which data values in a sample accurately represent the whole of that which is to be measured (10). The difference between completeness (or availability) and coverage is that completeness principally refers to the temporal aspect and coverage refers to the spatial aspect of traffic monitoring.

For example, the coverage of a data set could be 99% of the freeway system with continuous data collection (24 hours per day, 365 days per year). However, if there is missing data at some locations, the completeness value will fall below 99%. In this case, the data archive contains data less than the 99% that should be available from the given coverage of 99% of the total freeway system.

3.5. Discussion

This chapter has identified several issues regarding traffic data quality from intelligent transportation systems. Accuracy, availability, and coverage were considered as possible measures for assessing data quality. Of course, there are many other criteria for data quality (16, 17) such as accessibility, how easy can the data retrieved and manipulated by data customers to meet their goals, and logical consistency, to clarify contradictory relationships in the database, that can be examined in future studies. However, the project was focused on the above-mentioned criteria that were clarified as the most significant for the needs of evaluating the network of roadway sensors at I-80/94 Borman Expressway.

CHAPTER 4. QUALITY CONTROL PROTOCOL

4.1. Introduction

One of the project objectives is to document quality control procedures, that an agency can use to evaluate the performance of various detection technologies. To achieve this goal, a test site located on I-465 (Indianapolis) was used and several tests were made to assess the continuity and the consistency of the data reported by microloops and RTMS sensors. The objectives of the evaluation were:

- Assess how well the detectors could perform in typical installations
- Identify installation requirements and limitations
- Understand how to use the equipment in the most effective way
- Develop evaluation criteria

4.2. Description of I-465 test site and evaluation procedure

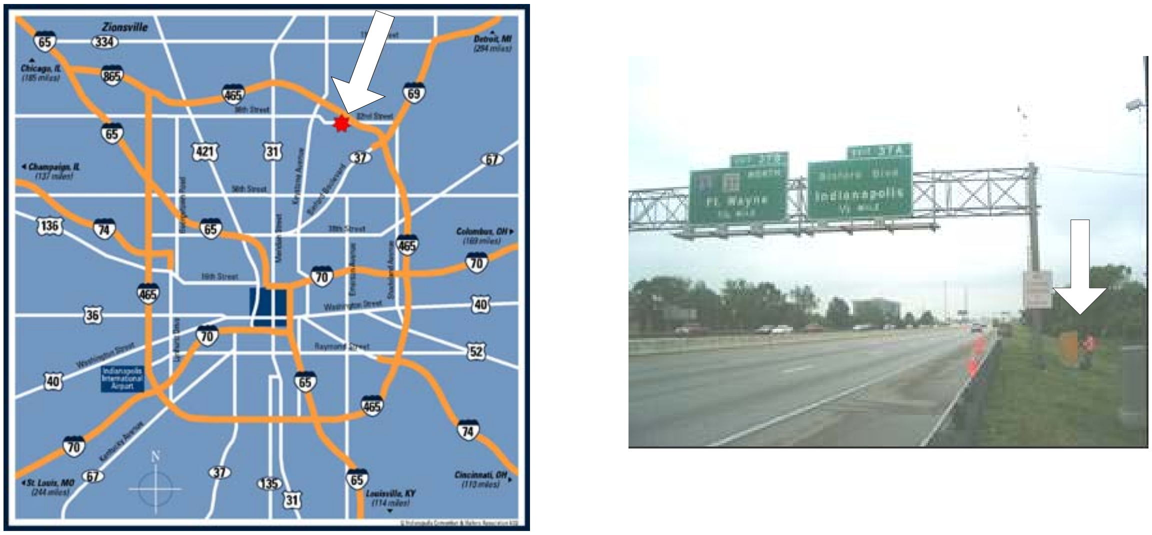
4.2.1. Site geometry and configuration

The test site is located on the eastbound direction of I-465, at Mile Post (M.P.) 36.2 as shown in Figure 4-1. The selection of the test site was made based on two criteria:

- Access to the site
- Ease to use the available instrumentation in the particular location

At this site, there are three 12 feet lanes that carry approximately 60,000 - 65,000 vehicles for the eastbound direction per day, and a shoulder lane. The test site was equipped with non-invasive microloops in all lanes and a roadside-mounting pole that the RTMS was placed at about 17' height. Figure 4-2 illustrates the configuration of the microloops and RTMS that existed during the analysis period. The detector spacing was estimated by calibrating the microloops with the use of a laser gun. The initial calibration was done before the start of the first data collection and indicated that there was a significant difference between the detector spacing in lane 2 (18.6

feet), and the detector spacing in lanes 1 and 3 (21.0 and 21.7 feet, respectively). This inconsistency will be discussed in more detail in Chapter 5.



a) Map Location b) Site Photo

Figure 4-1: Study site

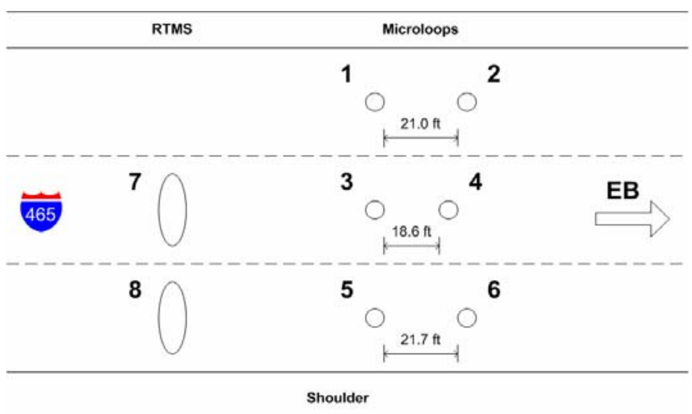
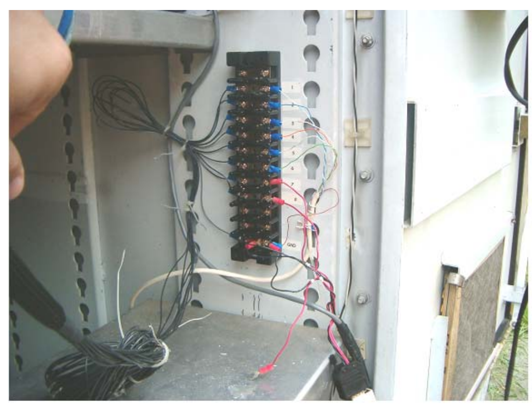


Figure 4-2: Configuration of microloops and RTMS with initial detector spacing

At the location, the equipment was located in two closely spaced cabinets as shown in Figure 4-3a and b. For the both technologies, the wires routed through the conduits and were lead to the second cabinet where they terminated to the terminal strip. Therefore, we had two options for providing data; a) directly over a serial bus and b) by “contact outputs” that simulate loop detector outputs from the traffic controller (Autoscope 2020) input files as depicted in Figure 4-3b and Figure 4-3c. Both options were applied for the two technologies. However, for this second option for the RTMS we could receive data only for two lanes, because only eight outputs were available for use.

a) Cabinets photo

b) Loop output in cabinet 1



c) Autoscope input in cabinet 2

Figure 4-3: Wires from cabinet 1 to cabinet 2

The basic equipment that was located in cabinet 2 and was used for the evaluation includes: (Figure 4-4).

A. Video Interface Panel

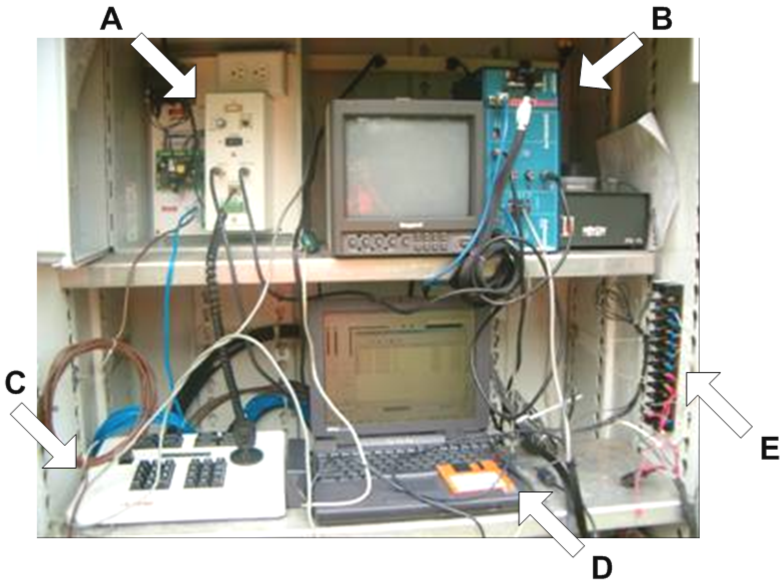
B. Autoscope 2020

C. Video Controller

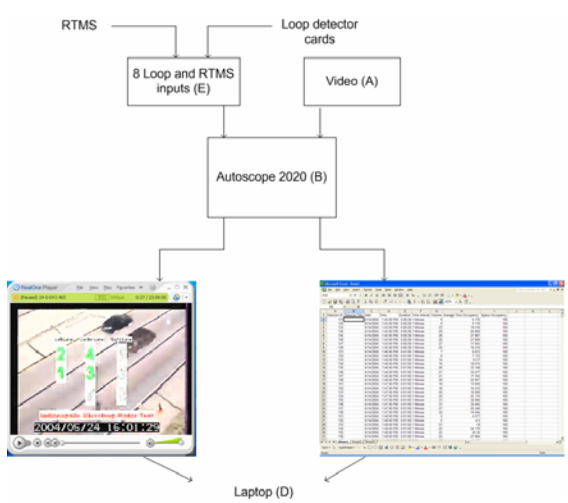
D. Laptop Computer with all necessary software (Autoscope detector software, Helix Producer, 3M ITS Link, Win RTMS 2.0, Receive Delta, Microsoft Excel)

E. Loop and RTMS inputs

In cabinet 1, only the Canoga traffic monitoring cards were placed together with a second laptop to upload the collected data.



a) Photo of the equipment in the cabinet



b) Block Diagram

Figure 4-4: Equipment used for the evaluation

4.2.2. Data collection

The data collection through the serial ports of the detectors was very simple as the only requirement was to install the proper software and download the reported data for volume, occupancy and speeds) from the traffic monitoring cards and the RTMS into the laptop. The data collection procedure through the Autoscope 2020 was more complicated but provided a mechanism for visually viewing the traffic condition when errors occur. The Autoscope data collection steps were as follows:

- From the terminal strip, microloop, radar and video inputs were plugged in to the Autoscope (Figure 4-4a, Point E)
- The laptop was then connected to the Autoscope and the detector file was set up (Figure 4-4a, Point D)
- On the screen, an overlay was placed so that the detectors are easily recognized (Figure 4-5)
- Outputs from Autoscope were lead to the laptop, which logged the counts for volume and occupancy
- 24-Hour Video was recorded to the laptop using video capture software
- Using the log text file, results were extracted to a spreadsheet
- By viewing the video, data was groundtruthed and graphs were produced for results comparisons

Figure 4-5 presents a screen capture of the video overlay of detector status with the approximate location of microloops (indicated by the small white circles). In the screen capture we can notice that channels 1, 2, 3 and 4 are ON (indicated by the green numbers) as there are two vehicles at this time on lanes 1 and 2, respectively.

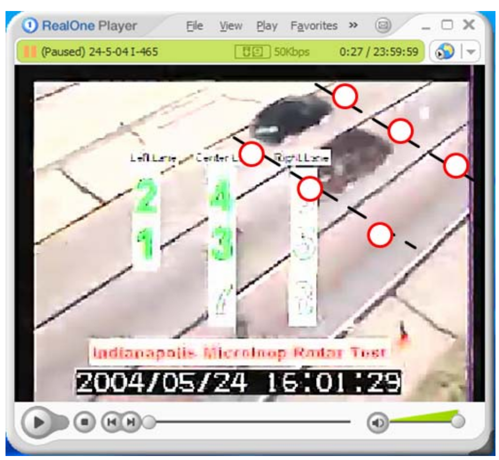


Figure 4-5: Screen capture of the video overlay of detector status with approximate location of microloops shown (Channels 1, 2, 3 and 4 are ON)

A time sequence example of vehicle detection for the test site, shown schematically in Figure 4-6, is depicted in Figure 4-7. On the video overlay shown, there are eight numbers representing the microloops and RTMS sensors at the site location, as follows:

- Numbers 1 and 2 correspond the leading and lagging microloops, respectively, in the left lane (Lane 1)
- Numbers 3 and 4 correspond the leading and lagging microloops, respectively, in the center lane (Lane 2)
- Numbers 5 and 6 correspond the leading and lagging microloops, respectively, in the right lane (Lane 3)
- Numbers 7 represents the RTMS sensor in the center lane (Lane 2)
- Numbers 8 represents the RTMS sensor in the right lane (Lane 3)

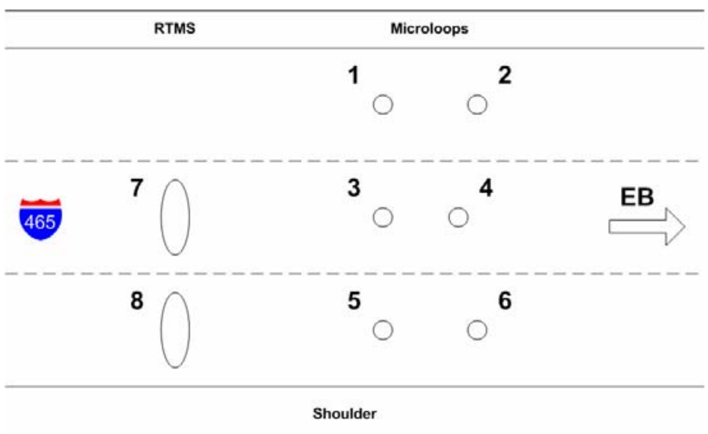
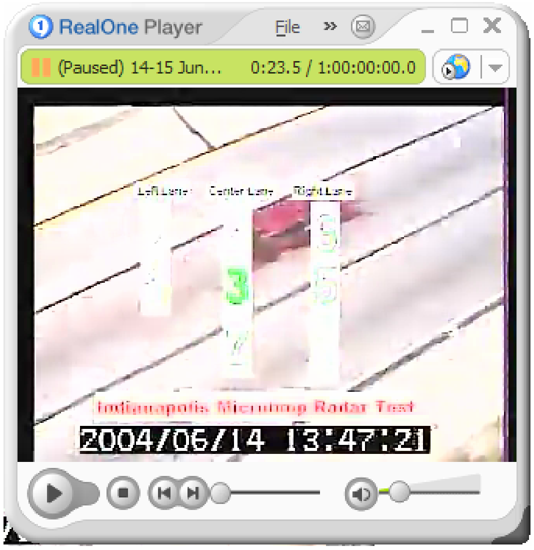
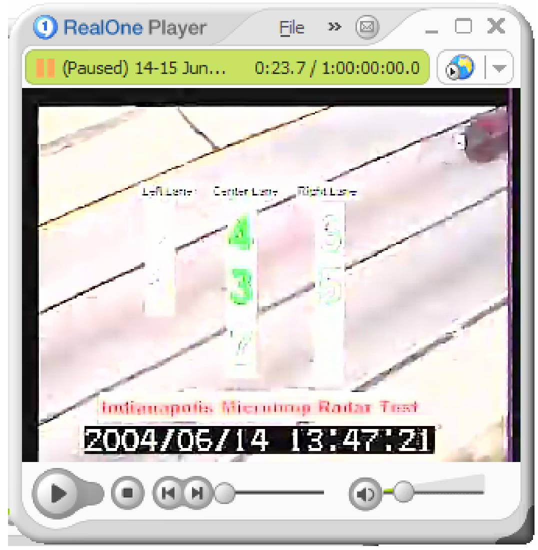


Figure 4-6: Site configuration

At the time that the vehicle passes over the lead detector, number 3 turns “ON” ,indicating a vehicle detection in lane 2 (Figure 4-7a). As the vehicle continues its way, number 4 turns “ON” to indicate that the vehicle passes over the lag detector of lane 2, as well (Figure 4-7b). A few hundreds of seconds later, number 3 turns “OFF”, resulting that the vehicle is not within the detection zone of the leading microloop any more (Figure 4-7c). However, the vehicle is still in the detection zone of the lagging microloop. Finally, as shown in Figure 4-7d, the vehicle gets out of the detection zone of the lagging detector, and at the same time, the RTMS sensor indicates that another vehicle (not shown in the figure) is detected and is expected to pass over the microloops in the next few seconds.



a) Channel 3 is ON and channel 4 is OFF



b) Both channel 3 and channel 4 are ON

c) Channel 3 is OFF and channel 4 is ON

d) Both channel 3 and channel 4 are OFF

Figure 4-7: Example of vehicle detection on channel 3 and 4 in lane

4.2.3. As-built diagram

One issue that arose at the data collection procedure on I-465 was that there was not an accurate plan to depict important construction and configuration parameters such as offsets, spacing between probes, depth of the probes and height of the RTMS sensor. Although, for example, the problem of the microloops distance can be addressed to some extent with calibration procedures with the use of a laser gun, other problems that can affect the accuracy of the data cannot be easily measured, after construction is complete.

For instance, after the data collection of June 14-15, 2004, it was observed that for the center lane (lane 2) there were significant discrepancies concerning the vehicle counts between RTMS, microloop and visual counts. Figure 4-8 illustrates that the results between microloops 3 and 4 were different by more than 1200 vehicles for the particular day.

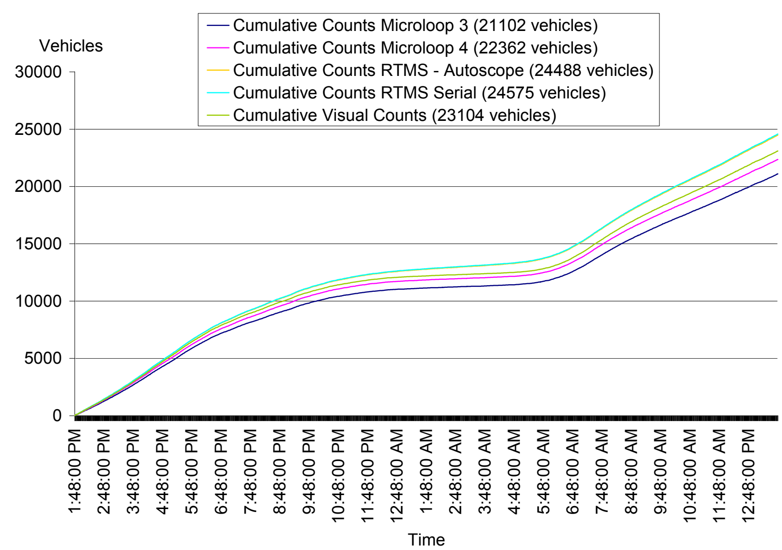


Figure 4-8: Cumulative microloop (Autoscope), RTMS (Autoscope and Serial) and visual counts for Lane 2, on I-465 at M.P. 36.2 on June 14-15, 2004

The waveform test and the change of inductance test that were performed several days later verified that the offsets of the center lane probes were not correct. In fact, when the probes were repositioned and the above-mentioned tests indicated more accurate results, data collection procedure was performed again to indicate a closer agreement between the results. Figure 4-9 illustrates that the results between microloops 3 and 4 were different by approximately 100 vehicles for the particular day.

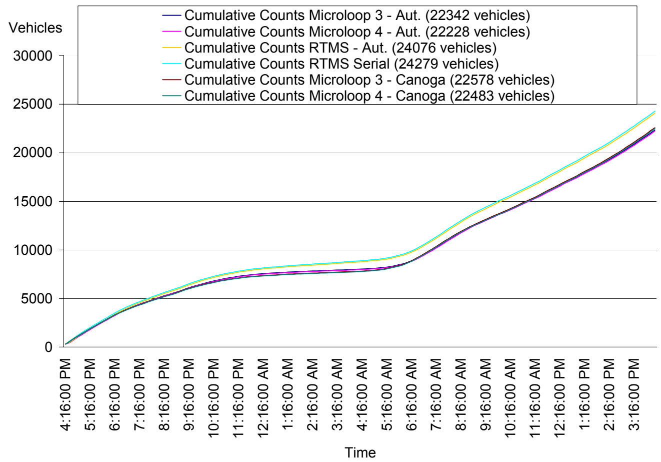


Figure 4-9: Cumulative microloop (Autoscope and Canoga) and RTMS (Autoscope and Serial) for Lane 2, on I-465 at M.P. 36.2 on July 13-14, 2004

To address problems like those mentioned above, this project proposes requiring as-built diagrams to ensure devices are installed according to vendor specifications. It is proposed that the contractor provides as-built drawings to document the in-place configuration.

For microloop detection technology, a proposed as-built diagram is depicted in Figure 4-10 and the associated dimension table is illustrated in Table 4-1. The table may include the following aspects:

- Width of lanes, shoulder and distance from edge of pavement to handhold
- Spacing between probes
- Depth measured from pavement surface to top of conduit
- Offset measured from edge of conduit in handhold to probe (see Figure 4-11)
- Description of any subsurface infrastructure (conduits, drains, pipes, utilities, culverts) within 25’ of any probe

For the RTMS technology, a proposed as-built diagram is depicted in Figure 4-12 and the associated table is illustrated in Table 4-2. The table may include the following aspects:

- Width of lanes, shoulder and distance from edge of pavement to RTMS
- Offset measured from RTMS to each lane
- Height of RTMS measured from grade at edge of travel lane

The as-built diagrams and the associated tables can be a useful maintenance tool especially for sites located in very congested highways such as I-80/94.

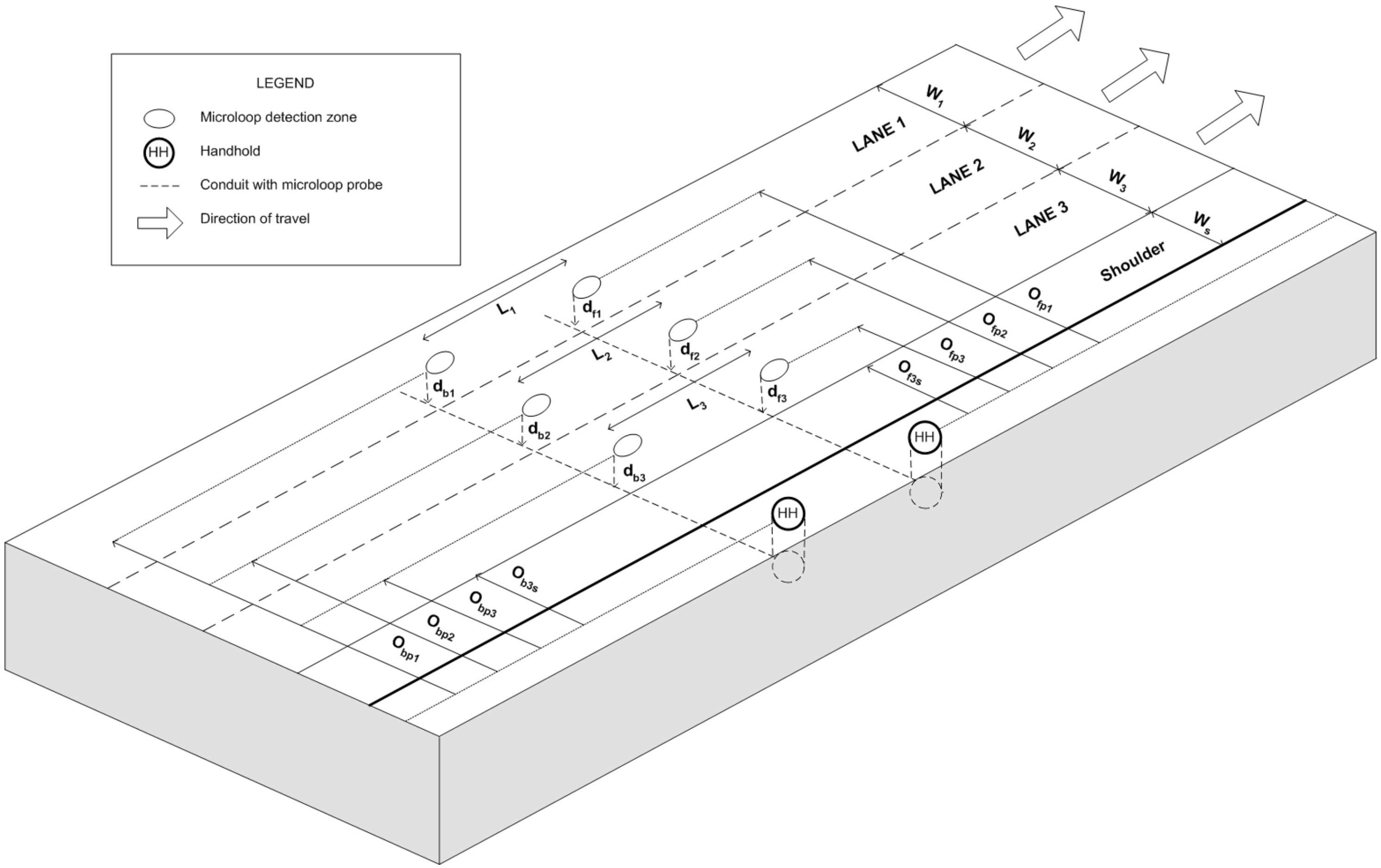


Figure 4-10: As-built sketch

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 4-11)	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					

Table 4-1: Legend of As-built sketch

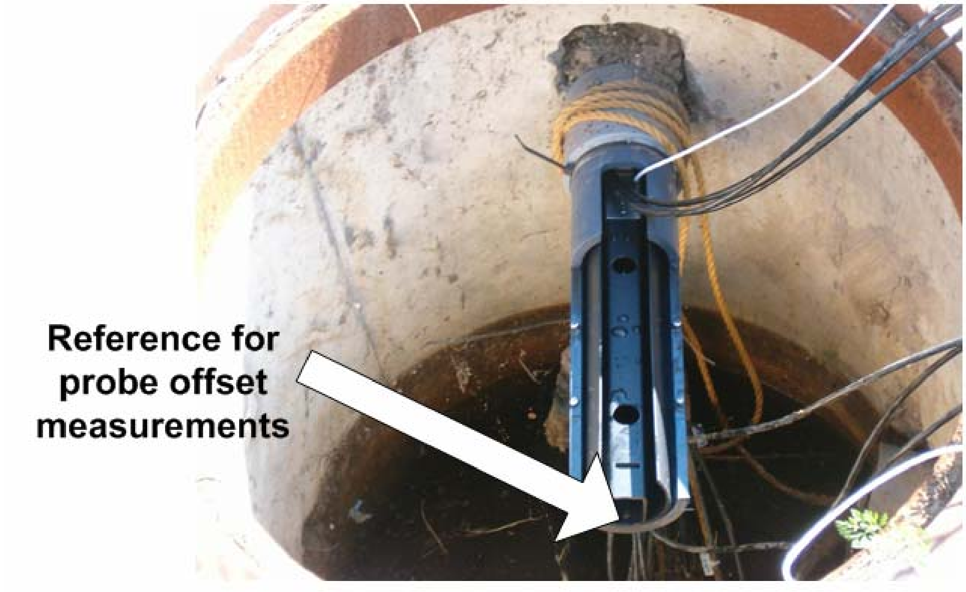


Figure 4-11: Edge of conduit in the handhold

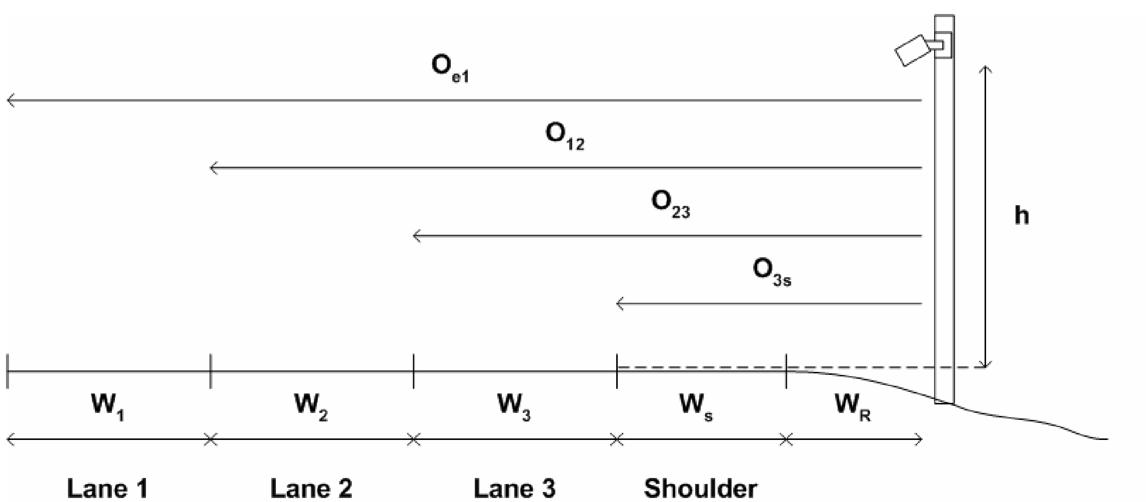


Figure 4-12: RTMS Offsets

Parameter Group	Symbol	Description	Expected Range	Manufacturer Tolerance	Actual Value
Width of lanes, shoulder and distance from edge of pavement to RTMS	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’		
	W_R	Distance from edge of pavement to RTMS			
Offset measured from RTMS to each lane	O_{e1}	Offset end-lane 1			
	O_{12}	Offset lane 1-lane 2			
	O_{23}	Offset lane 2-lane 3			
	O_{3s}	Offset lane 3-shoulder			
Height of RTMS measured from grade at edge of travel lane	h	Height of RTMS			

Table 4-2: Legend of RTMS offset sketch

CHAPTER 5. APPLICATION OF QUALITY CONTROL PROTOCOL

5.1. Description of I-465 test site's evaluation procedure

This project, based on the literature review, assesses the data quality of the non-invasive microloops and the RTMS sensor. To evaluate the performance of the detectors, the following tests were applied to the I-465 test site during the summer of 2004:

- Volume Comparisons
- Speed Comparisons
- Discrepancies in Occupancy
- Time “On” Comparisons
- Average Effective Vehicle Length (AEVL) test

Volume and speed comparisons are presented in this chapter, while the other three tests (discrepancies in occupancy, time “on” comparisons and average effective vehicle length test), which are related with occupancy, are discussed analytically in Chapter 6.

5.2. Volume comparisons

Simple cumulative 24-hour count graphs were produced, to evaluate the consistency of the 1-minute data reported by the microloops and the RTMS. To eliminate any possible discrepancies, data was taken directly from serial ports and from contacts connected to Autoscope 2020, as well.

The initial results revealed unexpected differences in vehicle counts between the leading and the lagging microloop in the middle lane. Figure 5-1 represents graphically the results of the volume comparison test performed for lane 2, on June 14-15, 2004 Notice that microloop 4 (lagging microloop) overcounted approximately 1200 vehicles in comparison with microloop 3 (leading microloop). In addition, microloop 3 counted approximately 2000 vehicles less than the visual counts; the percentage of error was -8.67%.

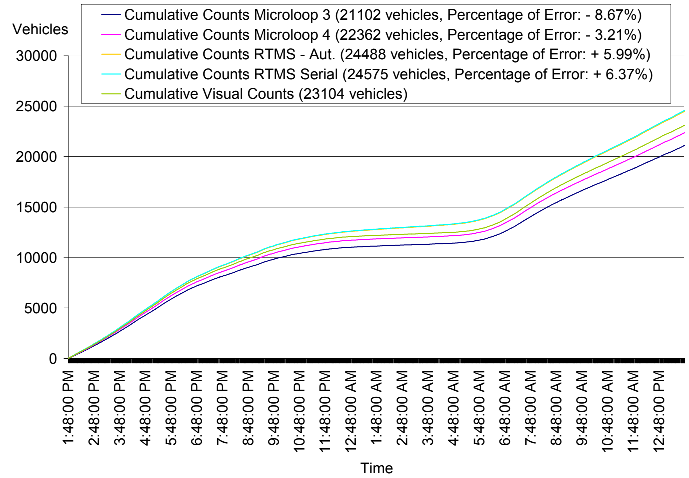


Figure 5-1: Initial volume comparison test on I-465, lane 2, June 14-15, 2004

To examine this inconsistency, a waveform analysis was used to screen for sensor noise problems and significant amplitude differences between the leading and the lagging microloop not only in the center lane, but in the other two lanes, as well.

The results of the waveform test for lane 1, depicted in Figure 5-2, did not reveal any noticeable discrepancies between the front and the back microloop.

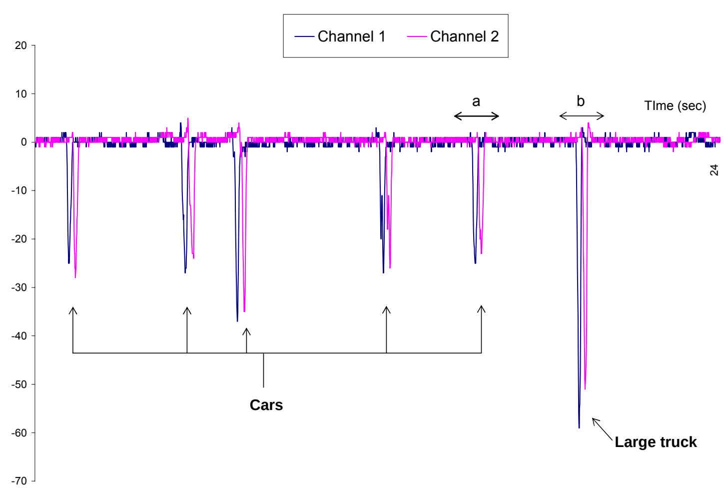


Figure 5-2: Microloop waveforms in Lane 1 at I-465 EB M.P. 36.2

In contrast, the waveform analysis of lane 2 indicated that there were large amplitude differences between the leading and the lagging microloop as illustrated in Figure 5-3. Several hypotheses were considered to explain this fact. The most reasonable explanations were that either a drainage tile was present under the surface of the pavement affecting the performance of the microloops, or the probe depths were inconsistent.

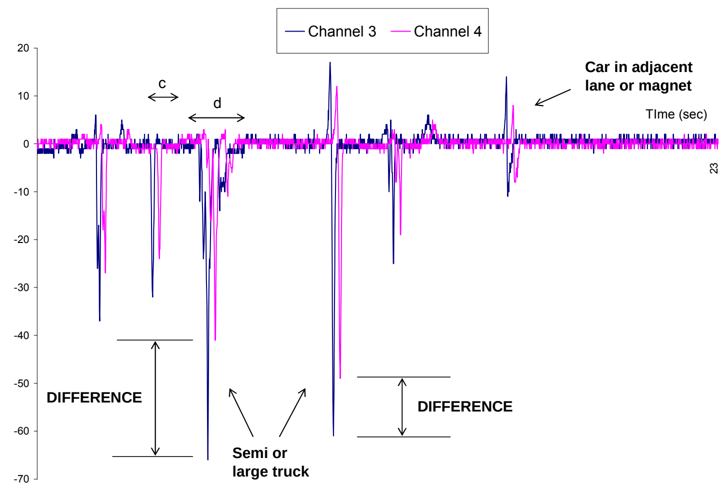


Figure 5-3: Microloop waveforms in Lane 2 at I-465 EB M.P. 36.2

The waveform analysis for lane 3, depicted in Figure 5-4, did not show any important indications, except for some noise problems probably because of the presence of a class-9 vehicle.

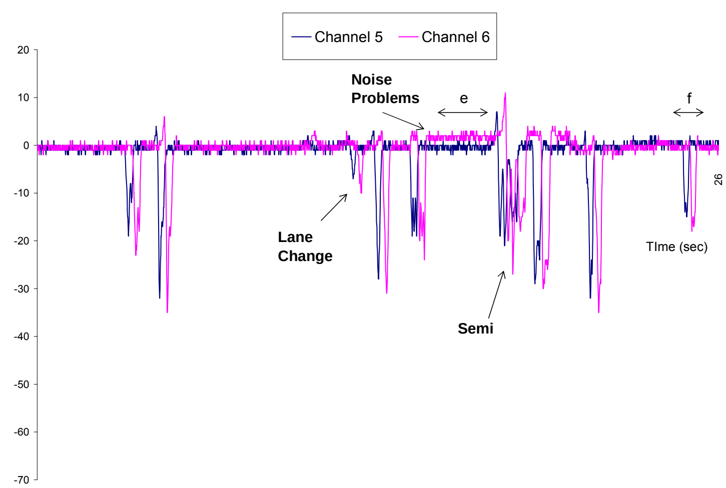
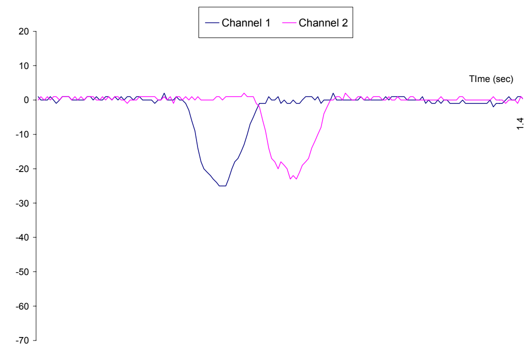
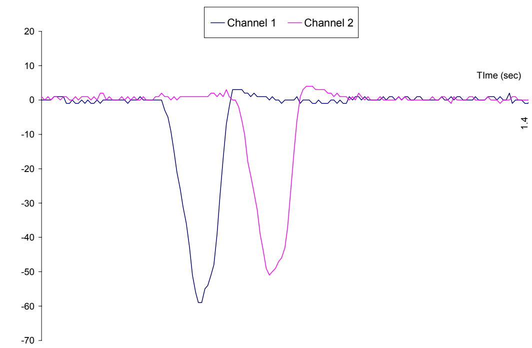


Figure 5-4: Microloop waveforms in Lane 3 at I-465 EB M.P. 36.2

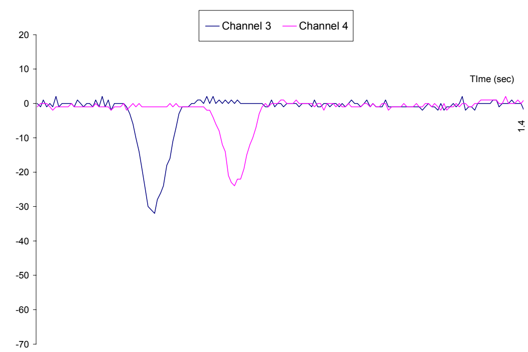
Figure 5-5 depicts more details on the way that the waveform analysis examined vehicle detection, noise problems and differences in magnitude between leading and lagging microloops.



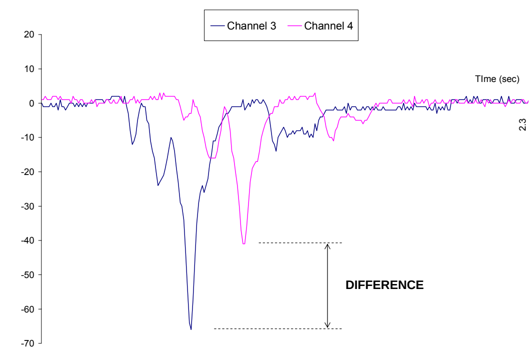
a) Example lane 1 car detection



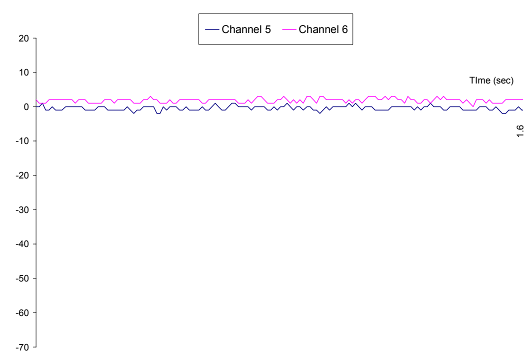
b) Example lane 1 large truck detection



c) Example lane 2 car detection



d) Example lane 2 class-9 vehicle detection



e) Example lane 3 noise

f) Example lane 3 car detection

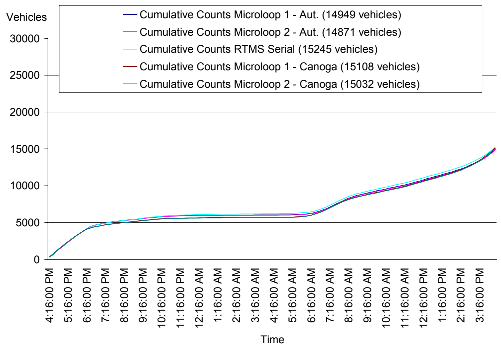
Figure 5-5: Indications of vehicle detection and noise problems in waveform graphs

After the waveform test's indications, the decision was made to reposition the probes and assess again the performance of the microloops. The verification test was to count manually 100 vehicles in every lane, and then compare the results to event counts logged on the computer. As a result, the spacing was adjusted to give the correct volume measurement.
Table 5-1 shows the results of the calibration procedure before and after the repositioning of the probes. It can be observed that the difference between the results of lane 2 comparing to the other two lanes was significantly reduced after the waveform documentation procedure.

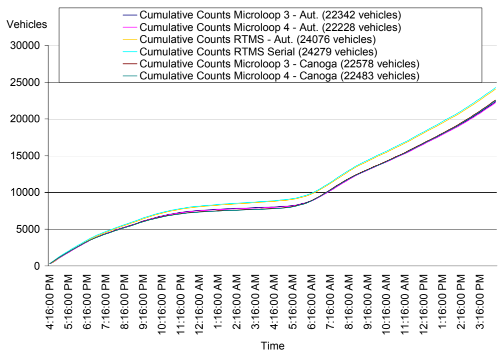
	Effective offset between lead and lag microloop (ft), May 24, 2004	Effective offset between lead and lag microloop (ft), July 9, 2004
Lane 1	21.0	20.4
Lane 2	18.6	19.4
Lane 3	21.7	20.2

Table 5-1: Calibration procedure results

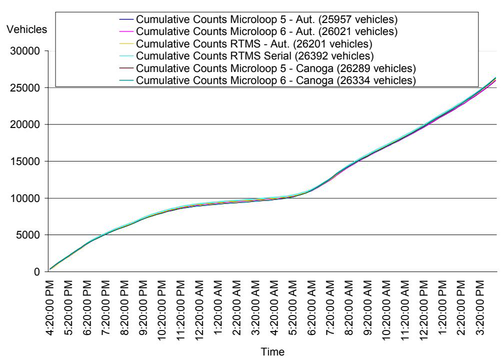
Figure 5-6 and Figure 5-7 depict the cumulative vehicle counts, after the probes were repositioned, provided by microloops and RTMS on July 13-14 (left column) and July 22-23, 2004 (right column), respectively. Microloop data was collected from Autoscope and the Canoga traffic monitoring cards for each probe, whereas RTMS data was collected by Autoscope and directly from serial port. The results indicated a very good agreement for lane 1 and lane 3 results, between RTMS and all microloop channels. On the other hand, discrepancies of about 1500 vehicles per day were observed between microloop and RTMS results for lane 2. However, results for the same technology (microloop or RTMS) for the two different channels were very close. Another important issue observed was that the differences between microloop 3 and microloop 4 were significantly reduced to approximately 100 vehicles, comparing to the data taken on June 14-15, 2004, were the differences were approximately 1200 vehicles (Figure 5-1).



a) Lane 1

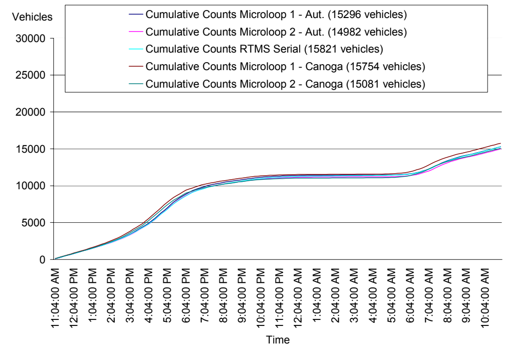


b) Lane 2

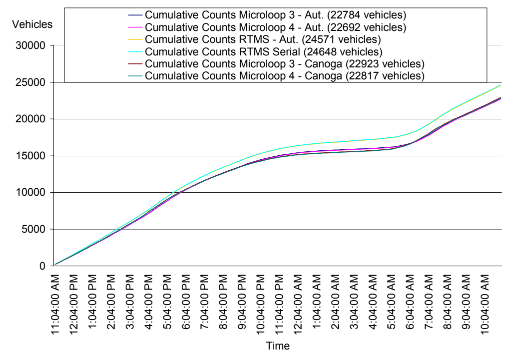


c) Lane 3

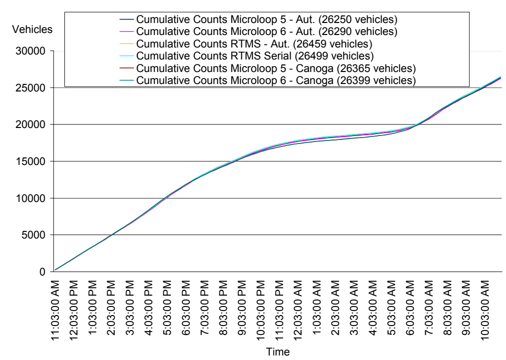
Figure 5-6: Cumulative microloop (Autoscope and Canoga) and RTMS (Autoscope and Serial) on I-465 at M.P. 36.2 on July 13-14, 2004



a) Lane 1



b) Lane 2



c) Lane 3

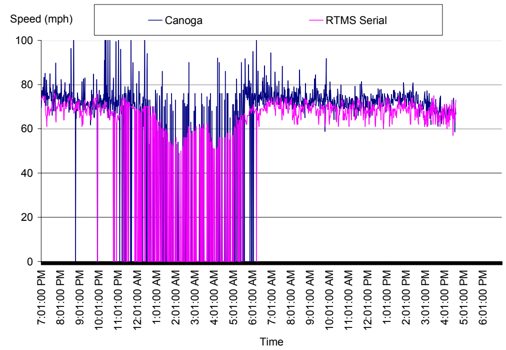
Figure 5-7: Cumulative microloop (Autoscope and Canoga), RTMS Autoscope, and Serial (6 ft loop emulation) on I-465 at M.P. 36.2 on July 22-23, 2004

5.3. Interpretation of speed comparisons

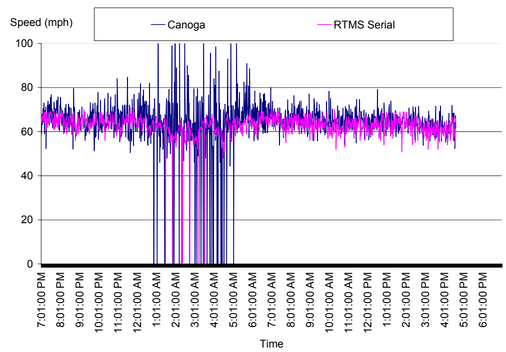
Similar procedure was followed to evaluate the 24-hour speed data. Results are presented for two different sets of 24-hour data. The results indicated that both detectors performed consistently for the daytime periods. However, for the nighttime period 00:00 - 06:00, the lack of data, due to low traffic volumes, complicated the analysis. The results of the speed comparisons are depicted in Figure 5-8 to Figure 5-20.

Analytically:

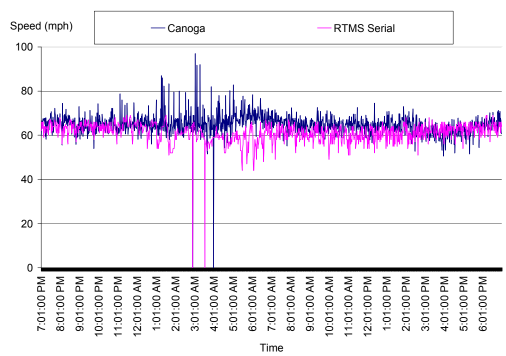
- Figure 5-8 and Figure 5-9 depict 24-hour speed comparisons for microloops and RTMS on July 1-2 (left column) and July 9-10, 2004 (right column), respectively.
- Figure 5-10 and Figure 5-11 depict the previously mentioned comparisons with all zero values deleted. This analysis makes the graph observation much easier.
- Figure 5-12 and Figure 5-13 depict 1-hour speed comparisons (9:00 - 10:00 p.m.) for microloops and RTMS on July 1-2 (left column) and July 9-10, 2004 (right column), respectively.
- Figure 5-14 and Figure 5-15 depict 1-hour speed comparisons (9:00 - 10:00 a.m.) for microloops and RTMS on July 1-2 (left column) and July 9-10, 2004 (right column), respectively.
- Figure 5-16 and Figure 5-17 depict 1-hour speed comparisons (4:00 - 5:00 a.m.) for microloops and RTMS on July 1-2 (left column) and July 9-10, 2004 (right column), respectively.
- Figure 5-18 and Figure 5-19 depict the previously mentioned comparisons with all zero values deleted.
- Figure 5-20 depict 1-hour speed comparisons (6:00 - 7:00 p.m.) for microloops and RTMS on July 9, 2004, during a congestion period in lane 3, between 6:15 - 6:45 p.m.)



a) Lane 1

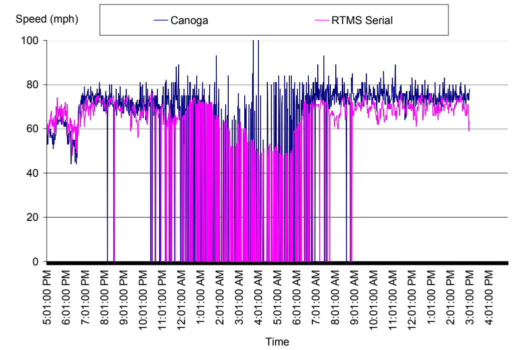


b) Lane 2

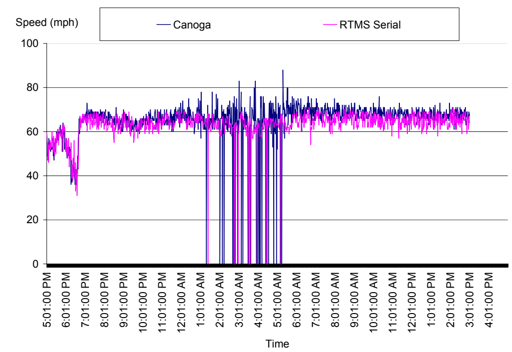


c) Lane 3

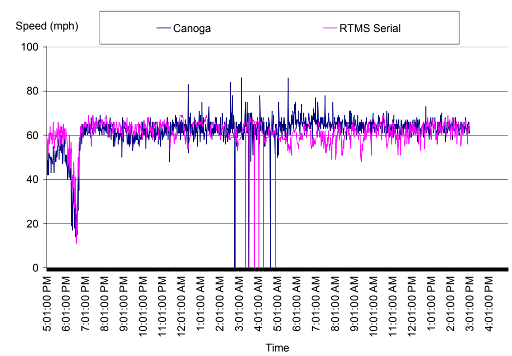
Figure 5-8: 24-hour speed comparisons for Microloop Canoga and RTMS Serial on I-465 at M.P. 36.2 on July 1-2, 2004



a) Lane 1

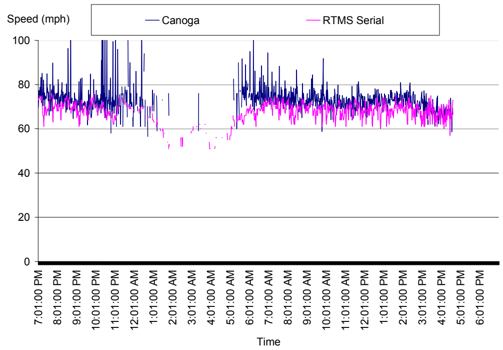


b) Lane 2

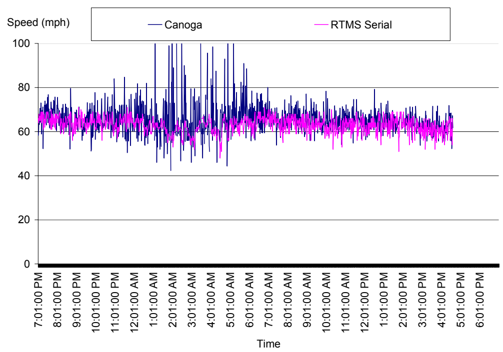


c) Lane 3

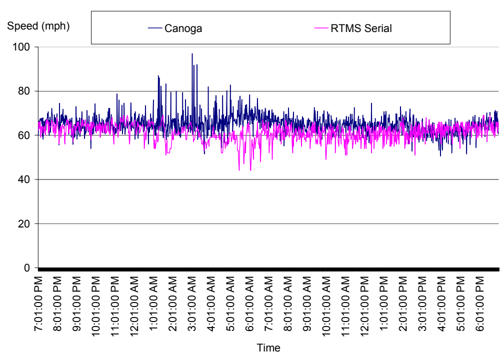
Figure 5-9: 24-hour speed comparisons for Microloop Canoga and RTMS Serial on I-465 at M.P. 36.2 on July 9-10, 2004



a) Lane 1

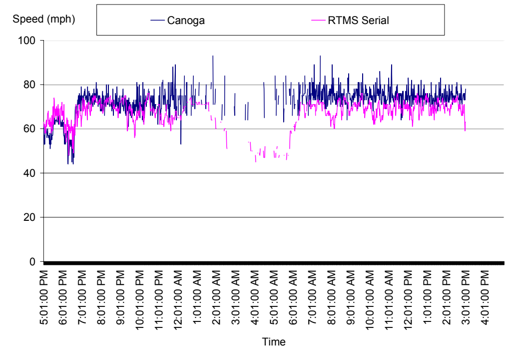


b) Lane 2

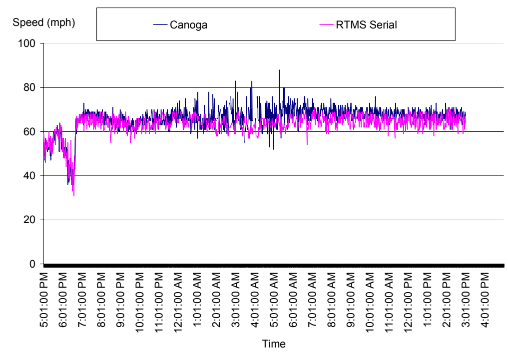


c) Lane 3

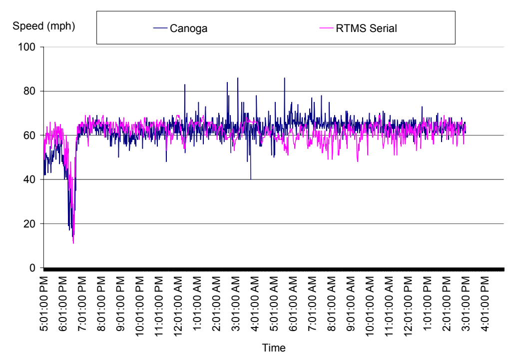
Figure 5-10: 24-hour speed comparisons for Microloop Canoga and RTMS Serial (all zero values deleted) on I-465 at M.P. 36.2 on July 1-2, 2004



a) Lane 1

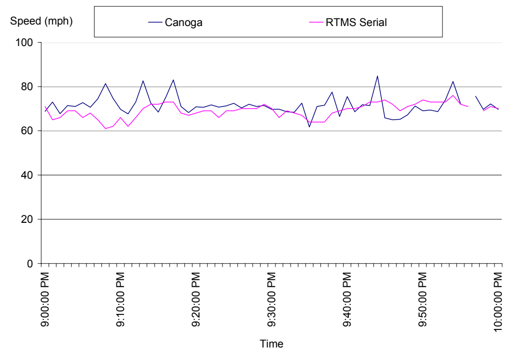


b) Lane 2

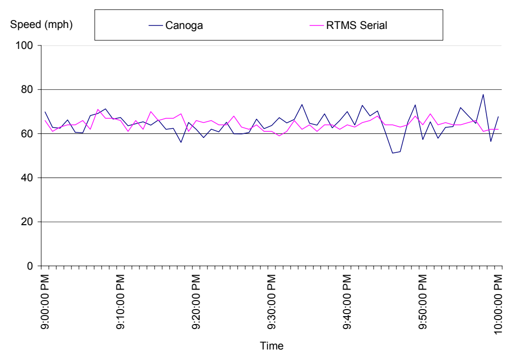


c) Lane 3

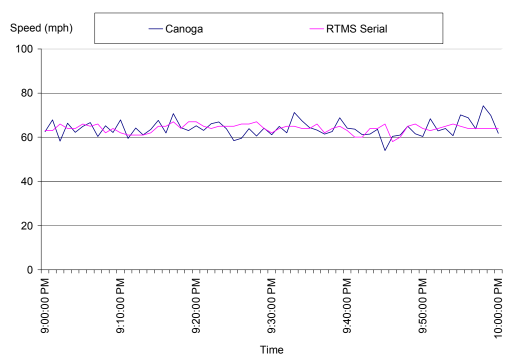
Figure 5-11: 24-hour speed comparisons for Microloop Canoga and RTMS Serial (all zero values deleted) on I-465 at M.P. 36.2 on July 9-10, 2004



a) Lane 1

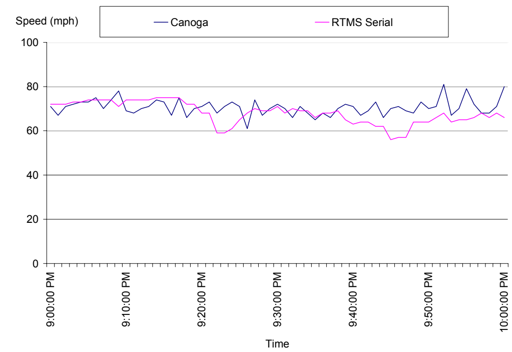


b) Lane 2

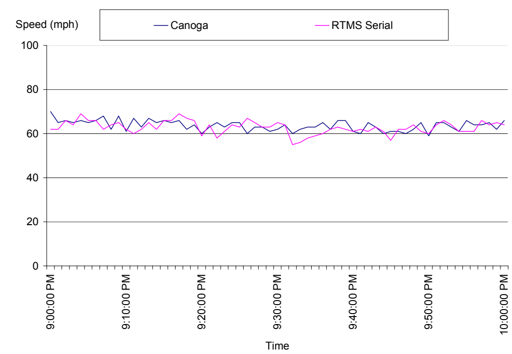


c) Lane 3

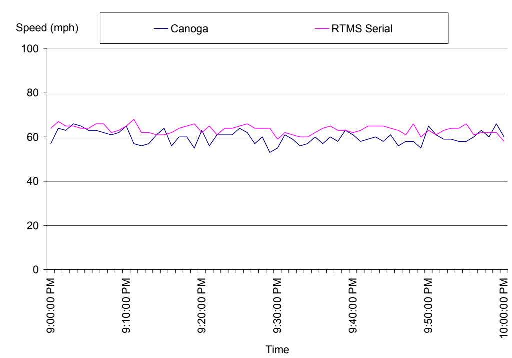
Figure 5-12: Speed comparisons for Microloop Canoga and RTMS Serial (9:00 – 10:00 pm) on I-465 at M.P. 36.2 on July 1, 2004



a) Lane 1

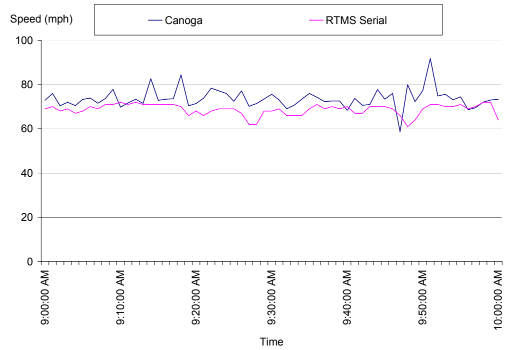


b) Lane 2

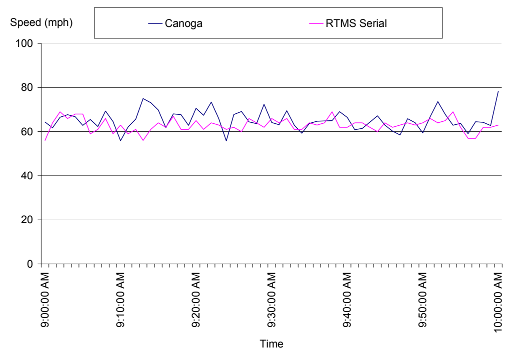


c) Lane 3

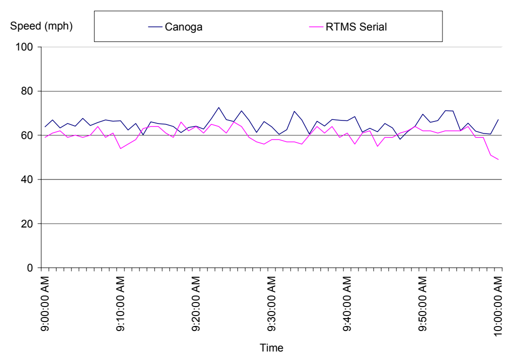
Figure 5-13: Speed comparisons for Microloop Canoga and RTMS Serial (9:00 – 10:00 pm) on I-465 at M.P. 36.2 on July 9, 2004



a) Lane 1

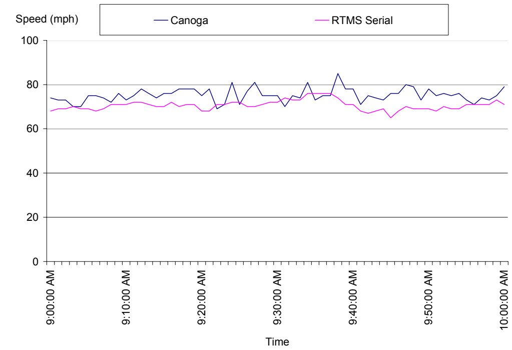


b) Lane 2

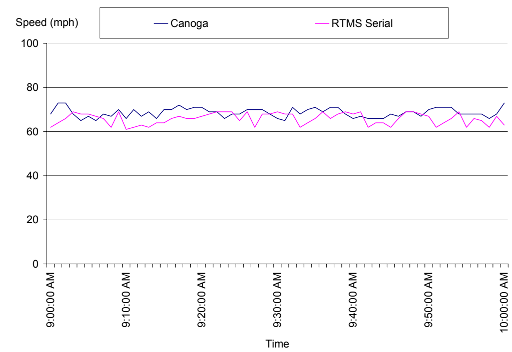


c) Lane 3

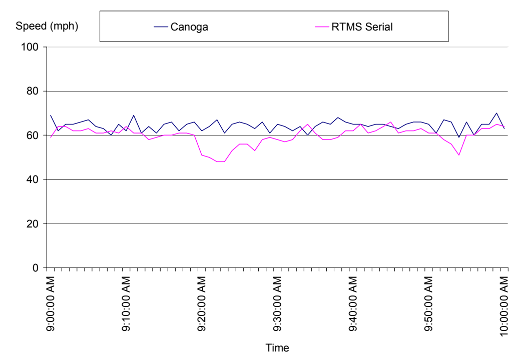
Figure 5-14: Speed comparisons for Microloop Canoga and RTMS Serial (9:00 – 10:00 am) on I-465 at M.P. 36.2 on July 2, 2004



a) Lane 1

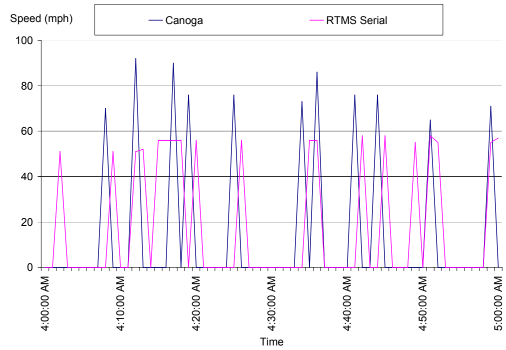


b) Lane 2

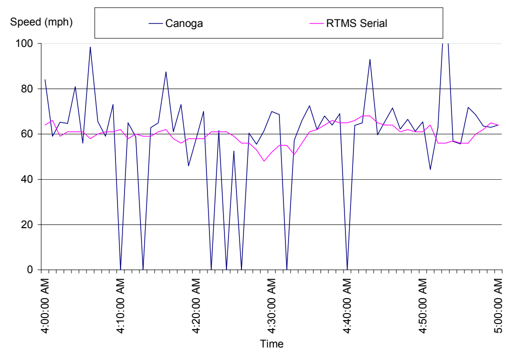


c) Lane 3

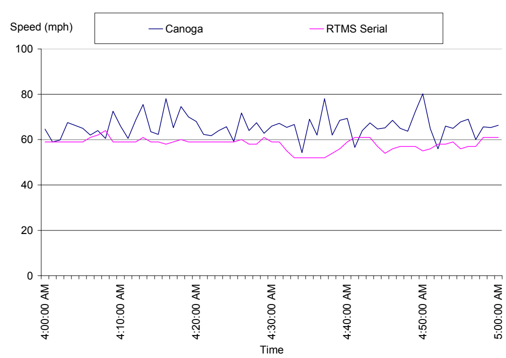
Figure 5-15: Speed comparisons for Microloop Canoga and RTMS Serial (9:00 – 10:00 am) on I-465 at M.P. 36.2 on July 10, 2004



a) Lane 1

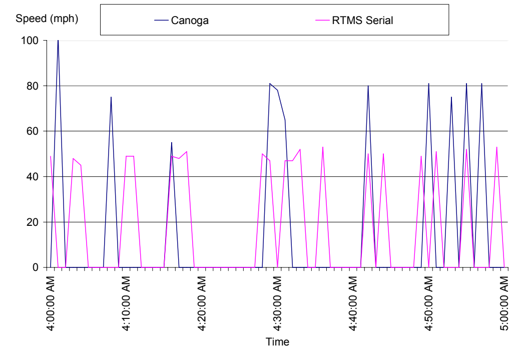


b) Lane 2

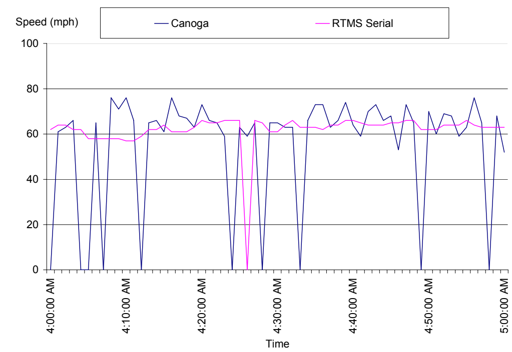


c) Lane 3

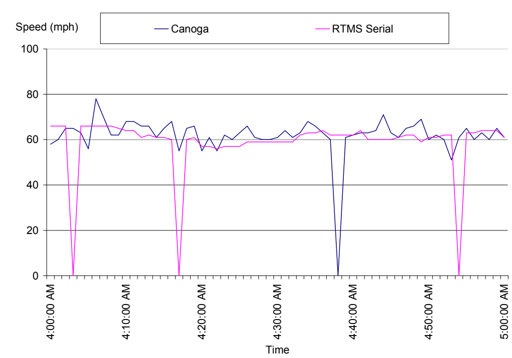
Figure 5-16: Speed comparisons for Microloop Canoga and RTMS Serial (4:00 – 5:00 am) on I-465 at M.P. 36.2 on July 2, 2004



a) Lane 1

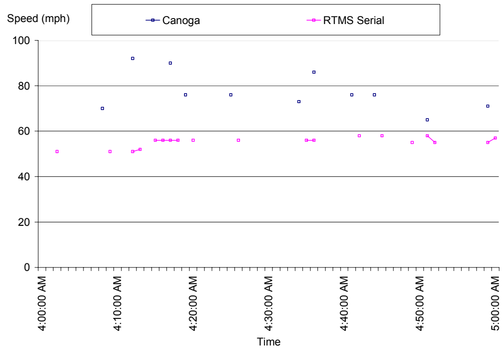


b) Lane 2

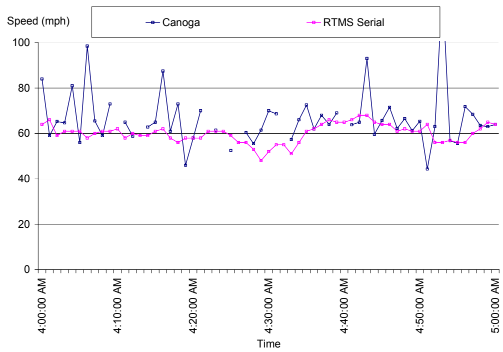


c) Lane 3

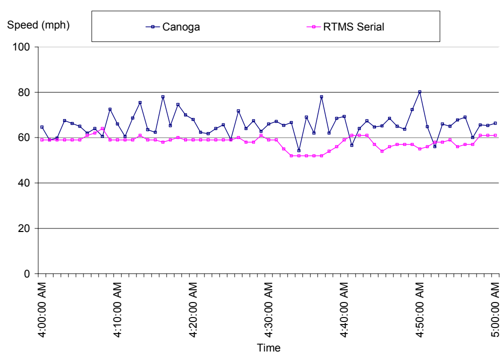
Figure 5-17: Speed comparisons for Microloop Canoga and RTMS Serial (4:00 – 5:00 am) on I-465 at M.P. 36.2 on July 10, 2004



a) Lane 1

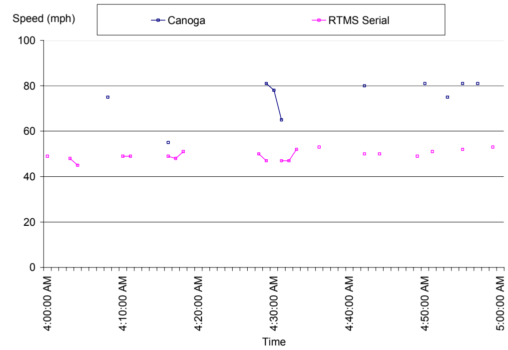


b) Lane 2

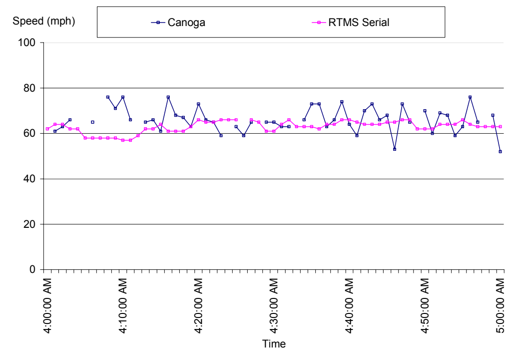


c) Lane 3

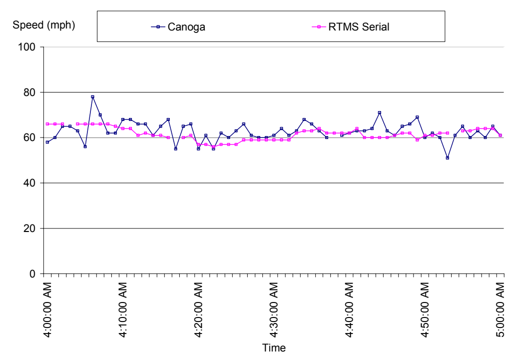
Figure 5-18: Speed comparisons for Microloop Canoga and RTMS Serial 4:00 – 5:00 am (all zero values deleted) on I-465 at M.P. 36.2 on July 2, 2004



a) Lane 1

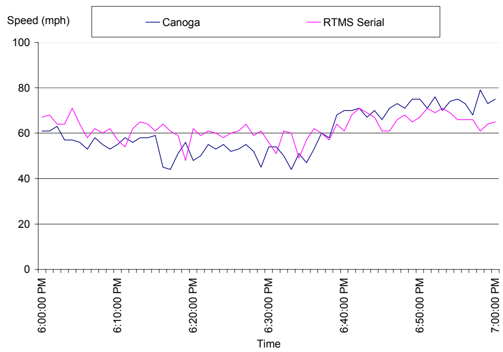


b) Lane 2

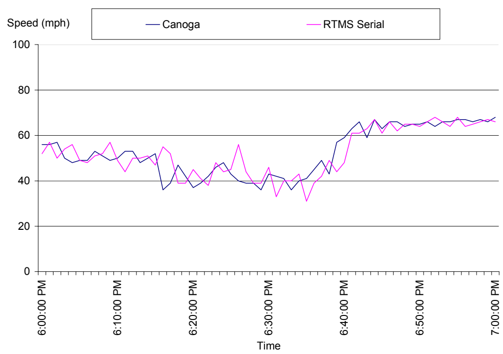


c) Lane 3

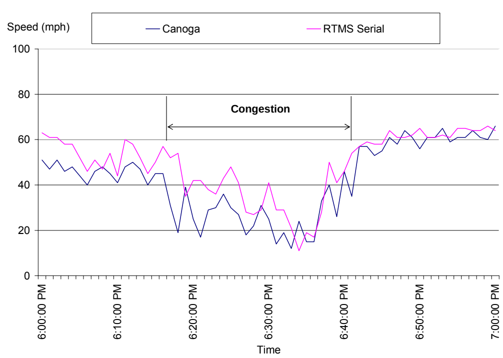
Figure 5-19: Speed comparisons for Microloop Canoga and RTMS Serial 4:00 – 5:00 am (all zero values deleted) on I-465 at M.P. 36.2 on July 10, 2004



a) Lane 1



b) Lane 2



c) Lane 3

Figure 5-20: Speed comparisons for Microloop Canoga and RTMS Serial (6:00 – 7:00 pm) on I-465 at M.P. 36.2 on July 9, 2004

5.4. Discussion

This chapter presented the results of the performance evaluation of microloops and RTMS sensor on I-465. Specifically, speed and volume comparison graphs, for 24-hour data, were used to reveal inconsistencies in the detectors' performance. The following chapter will examine data screening procedures using occupancy. Particularly, discrepancies in occupancy reported by two different detection technologies and the cumulative time that the detectors stayed "on" due to the presence of vehicles will be depicted in simple comparison graphs. In addition, another data quality metric, the average effective vehicle length test, will be discussed extensively, and the results of this test will be presented and analyzed.

CHAPTER 6. QUALITY CONTROL METRICS USING OCCUPANCY

6.1. Introduction

Another critical parameter that was examined during the quality control procedure was the occupancy reported by microloops and the RTMS sensors. Occupancy has been recently a debatable issue for the microwave vehicle detection system (MVDS) technology. As it was discussed in Chapter 3, a Caltrans evaluation (13), documented that MVDS technology was not found to be suitable for accurately measuring occupancy at 30-second or 5-minute intervals. This study investigates whether occupancy can be used in data quality metrics and proposes the following data quality procedures that use occupancy:

- Discrepancies in occupancy
- Time “On” comparisons
- Average Effective Vehicle Length (AEVL) test

6.2. Discrepancies in Occupancy

To capture any discrepancies in occupancy reported by different technologies, 24-hour occupancy data was collected from microloops and the RTMS sensor on I-465 and the results were compared by using simple graphs. The data comparison procedure can be described with the following steps:

a. 1-minute occupancy data was collected by microloops and RTMS sensor and matched up
b. Differences in occupancy between the two sensors were calculated
c. These differences were plotted in suitably designed graphs in which the acceptable limits denoted by Caltrans were also depicted.

According to Caltrans, data for occupancy can be considered valid, when the level of accuracy is approximately 95%.

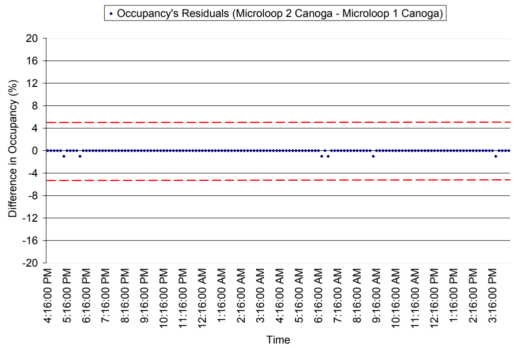
6.2.1. Interpretation of the results

In our case study, the evaluation procedure showed that when the detectors are installed and calibrated properly, the results for occupancy reported from microloop and MVDS sensors by RTMS are in good agreement.

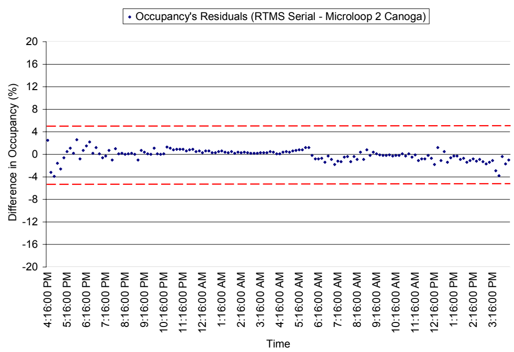
The following figures depict analytically the results of the tests:

- Figure 6-1 and Figure 6-2 depict differences in occupancy reported by microloops and RTMS in lane 1, on July 13-14, 2004 (left column) and July 22-23, 2004 (right column), respectively. Note that the RTMS for July 22-23, 2004, was set to capture occupancy as a 6-feet loop detector.
- Figure 6-3 and Figure 6-4 depict differences in occupancy reported by microloops and RTMS in lane 2, on July 13-14, 2004 (left column) and July 22-23, 2004 (right column), respectively.
- Figure 6-5 and Figure 6-6 depict differences in occupancy reported by microloops and RTMS in lane 3, on July 13-14, 2004 (left column) and July 22-23, 2004 (right column), respectively.

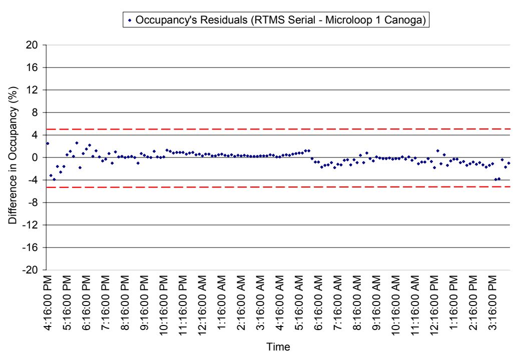
We can notice that for the data collected on July 13-14, 2004, for all lanes the discrepancies in occupancy reported by microloops and RTMS are between the boundaries of $\pm 5\%$. In addition, it seems that for lane 2, RTMS reported higher occupancy values comparing to the microloops. However, for the data collected on July 22-23, 2004 (where RTMS was set to capture occupancy as a 6-feet loop detector), RTMS tended to overestimate occupancy (particularly in lane 2), and many records are out of the Caltrans ($\pm 5\%$) boundaries. Therefore, we can conclude that a change in settings, on the way that a sensor capture and reports occupancy, can solve or (in our case) create inconsistencies.



a) Microloop 2 – Microloop 1 (Canoga)

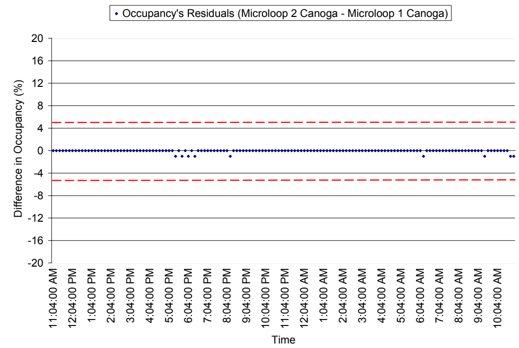


b) RTMS serial – Microloop 2 (Canoga)

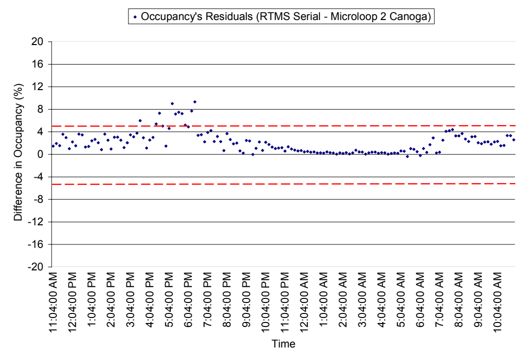


c) RTMS serial – Microloop 1 (Canoga)

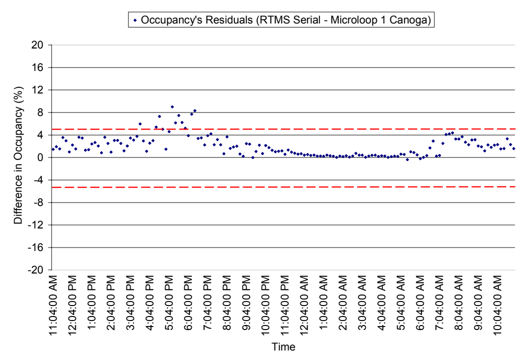
Figure 6-1: Difference in occupancy reported by microloops (Canoga) and RTMS serial in lane 1, on I-465 at M.P. 36.2 on July 13-14, 2004



a) Microloop 2 – Microloop 1 (Canoga)

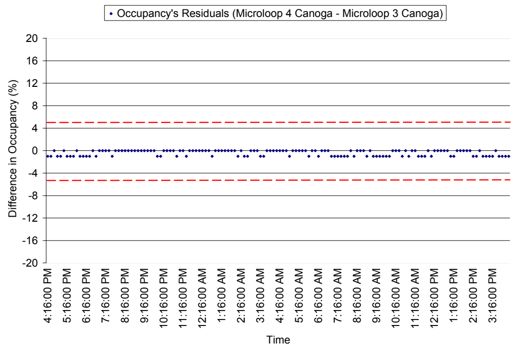


b) RTMS serial – Microloop 2 (Canoga)

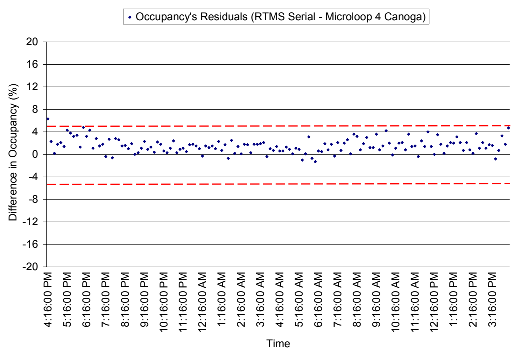


c) RTMS serial – Microloop 1 (Canoga)

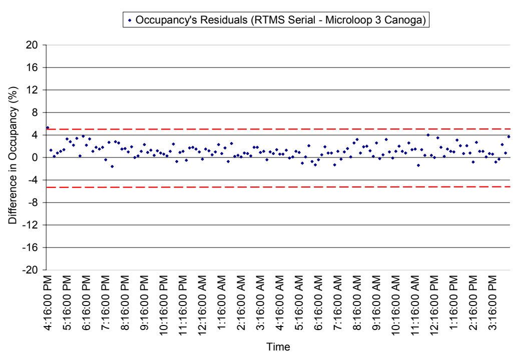
Figure 6-2: Difference in occupancy reported by microloops (Canoga) and RTMS serial (6 ft loop emulation) in lane 1, on I-465 at M.P. 36.2 on July 22-23, 2004



a) Microloop 4 – Microloop 3 (Canoga)

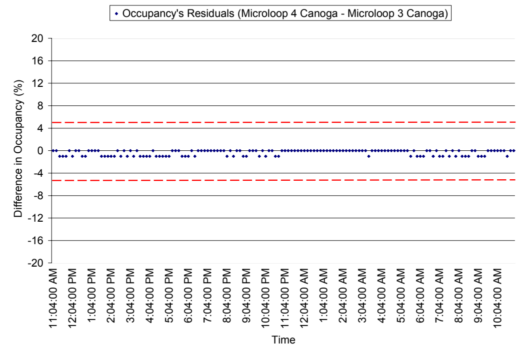


b) RTMS Serial –Microloop 4 Canoga

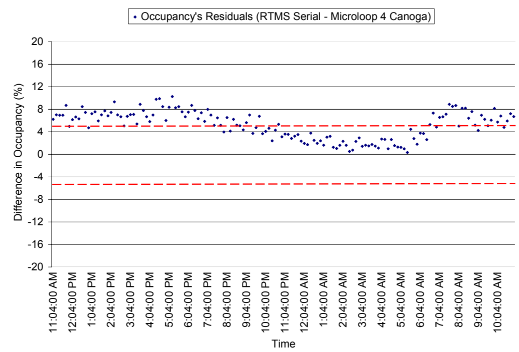


c) RTMS Serial –Microloop 3 Canoga

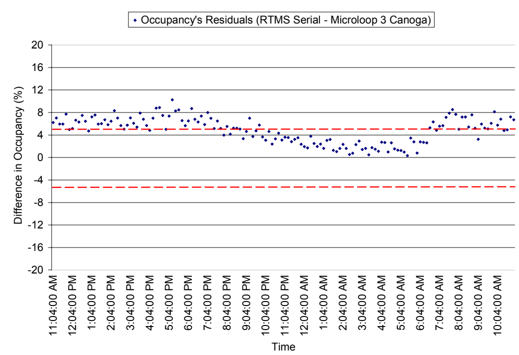
Figure 6-3: Difference in occupancy reported by microloops (Canoga) and RTMS serial in lane 2, on I-465 at M.P. 36.2 on July 13-14, 2004



a) Microloop 4 – Microloop 3 (Canoga)

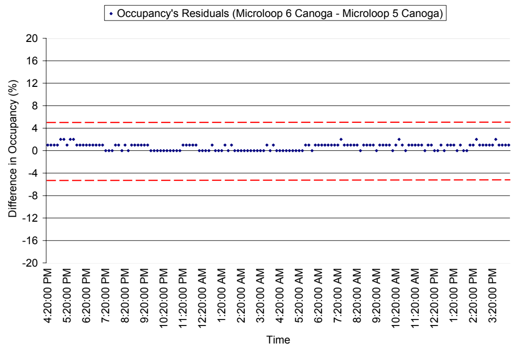


b) RTMS Serial –Microloop 4 Canoga

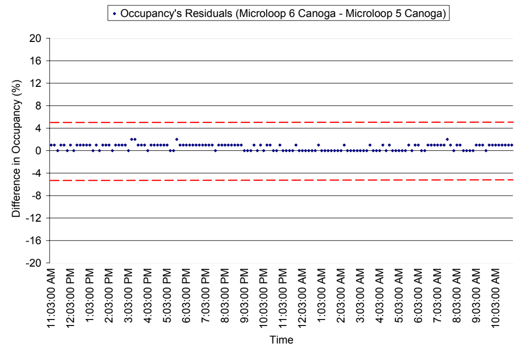


c) RTMS Serial –Microloop 3 Canoga

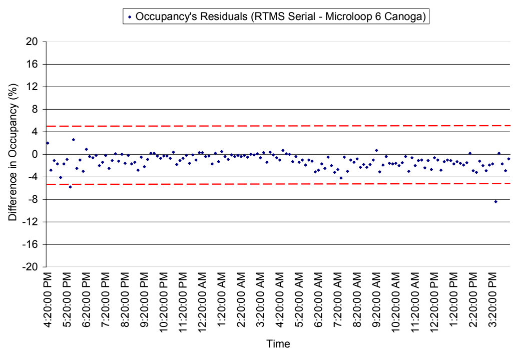
Figure 6-4: Difference in occupancy reported by microloops (Canoga) and RTMS serial (6 ft loop emulation) in lane 2, on I-465 at M.P. 36.2 on July 22-23, 2004



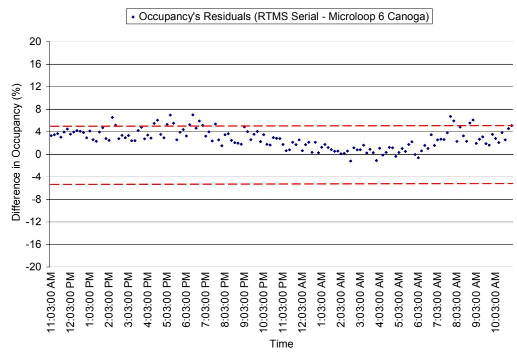
a) Microloop 6 – Microloop 5 (Canoga)



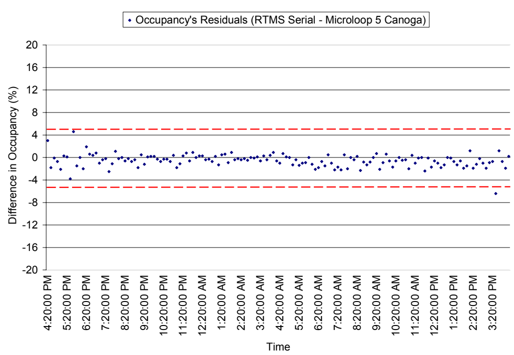
a) Microloop 6 – Microloop 5 (Canoga)



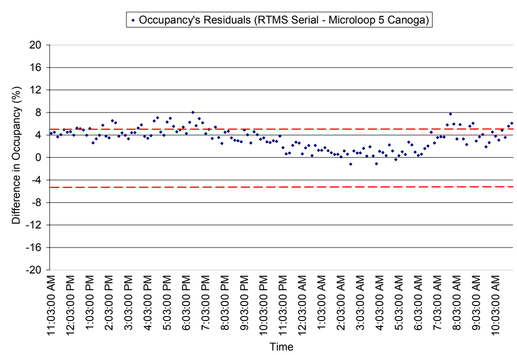
b) RTMS Serial – Microloop 6 (Canoga)



b) RTMS Serial – Microloop 6 (Canoga)



c) RTMS Serial – Microloop 5 (Canoga)



c) RTMS Serial – Microloop 5 (Canoga)

Figure 6-5: Difference in occupancy reported by microloops (Canoga) and RTMS serial in lane 3, on I-465 at M.P. 36.2 on July 13-14, 2004

Figure 6-6: Difference in occupancy reported by microloops (Canoga) and RTMS serial (6 ft loop emulation) in lane 3, on I-465 at M.P. 36.2 on July 22-23, 2004

6.2.2. "Time on" comparisons

A test, which was also applied, and was closely related to the reported occupancy, is the "Time On" comparison test. Based on the occupancy data, the time that the detector is "On" can be easily determined as follows:

$t_i = O_i * P$ (Equation 6.1)

Where:

O_i = Occupancy; Reported as a percentage

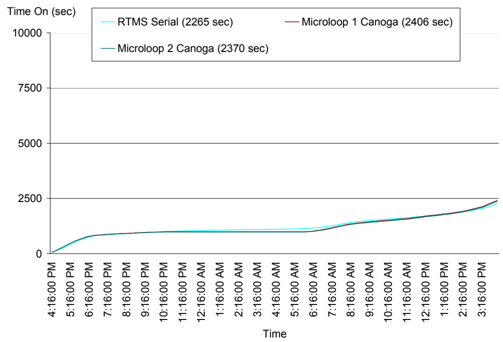
P_i = Sample Period; 1 minute

This test is a quantitative assessment of how close the data reported by each detector is. If we calculate the cumulative time that the sensors are "On" for the whole 24-hour period, possible trends or errors that may be hidden from the occupancy-comparison test, can be revealed.

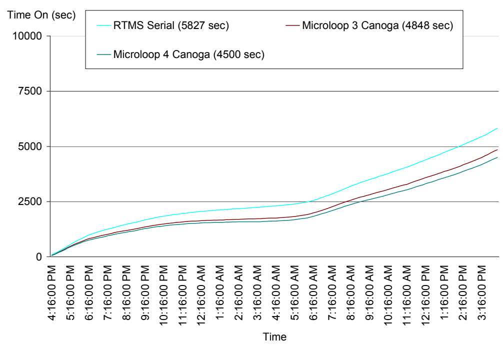
The results shown that the RTMS, in many cases, tends to overestimate occupancy in comparison to the microloops.

Figure 6-7 and Figure 6-8 depict the cumulative å t_i counts over 24 hours reported by microloops and RTMS, on July 13-14, 2004 (left column) and July 22-23, 2004 (right column), respectively. Note that the RTMS for July 22-23, 2004, was set to capture occupancy as a 6-feet loop detector.

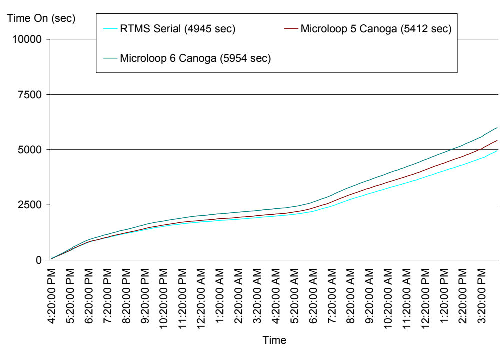
In this case, for July 22-23 data, RTMS tended to overestimate occupancy, particularly in lanes 2 and 3, whereas for July 13-14 data the differences were significantly smaller.



a) Lane 1

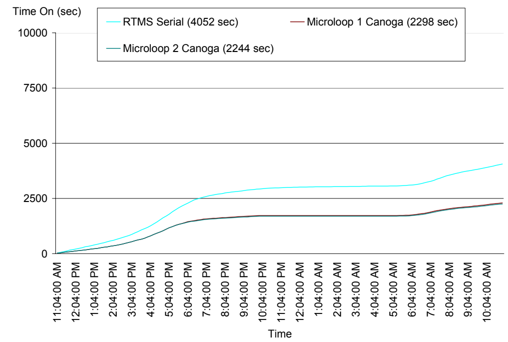


b) Lane 2

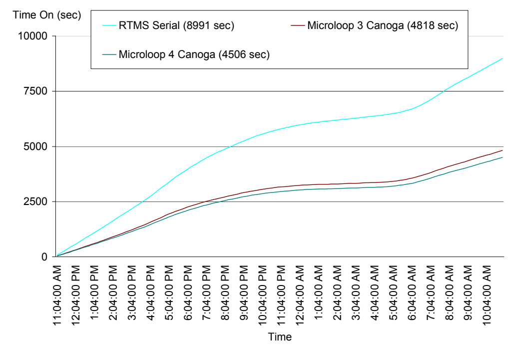


c) Lane 3

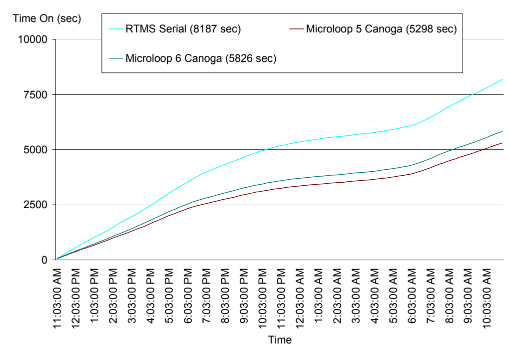
Figure 6-7: Cumulative microloop (Canoga), and RTMS Serial counts of detectors “on-time” status on I-465 at M.P. 36.2 on July 13-14, 2004



a) Lane 1



b) Lane 2



c) Lane 3

Figure 6-8: Cumulative microloop (Canoga), and RTMS Serial (6 ft loop emul.) counts of detectors “on-time” status on I-465 at M.P. 36.2 on July 22-23, 2004

6.2.3. Average effective vehicle length (AEVL) test

A procedure for screening detector data is the Average Effective Vehicle Length (AEVL) test (14), which examines a function of occupancy, volume and speed data for mining errors in individual records. AEVL can be calculated using traffic flow theory principles and has a range over which its values are feasible, based on the physical dimensions of the vehicles traveling on the freeway. Turochy and Smith defined AEVL as the sum of the vehicle length as observed by the detectors and detector length, measured in meters (14). AEVL can be calculated from the data by using the following formula:

$$AEVL = L_v + L_l = \frac{10*V*O}{q} \qquad \text{(Equation 6.2)}$$

Where

L_v = Length of the vehicle (m)

L_l = Length of the loop (m)

V = speed (km/h)

O = occupancy (percent)

q = hourly equivalent volume (vehicles/lane/hour)

The constant 10 results from the constant 1,000 (converts from km to m) divided by 100 (converts occupancy from percentage to decimal).

The test can be performed with data collected at stations that have paired loop detectors. Figure 6-9 shows how a pair of microloops acts like a speed trap to estimate occupancies and speeds.

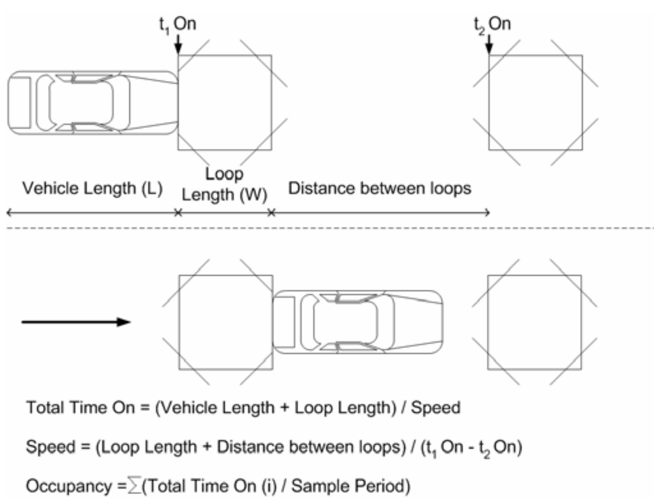


Figure 6-9: Speed Trap Illustration

Realistically, AEVL should not be less than 5 m (16.5 ft) [an average vehicle length of 3.2m (10.5 ft) plus a 1.8m (6 ft) detector]. However, the test is based on the assumption that a linear relationship is assumed between occupancy and density. This relationship is accepted to be linear under certain conditions (vehicle lengths, speeds and headways are considered fairly uniform and occupancies are between a range of 8-20%). According to the authors, this assumption was not considered to have a large impact on the calculation of AEVL, but to compensate their potential impact and reasonable error tolerances the minimum and maximum acceptable AEVL values were conservatively set to 2.7 m (9 ft) and 18 m (60 ft), respectively.

6.2.3.1. Investigation of Average Effective Vehicle Length (AEVL) relationship

In this example, it is examined whether AEVL is affected by the length and the speed of a vehicle that passes over the detector and how close the results of this test are compared to the average of “true” vehicle lengths.

From vehicle kinematics, it is known that when a vehicle passes over a detector, its length can be determined as follows:

$$L_{vi} = t_i * (V_i) - L_l \qquad \text{(Equation 6.3)}$$

Where:

L_{vi}: Length of vehicle i

V_i: Speed of vehicle i

L_l: Length of loop

t_i: Time that the first loop detector remains “On”

Figure 6-10 shows a vehicle with length (L_v) that passes over a loop detector with length (L_l)

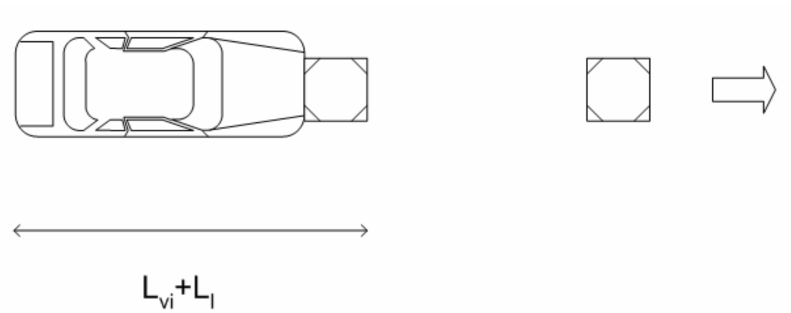


Figure 6-10: Vehicle passing over a loop detector

Suppose that i cars pass over the detector:

$L_{v1} + L_l = t_1 * (V_1)$ (Equation 6.4)

$L_{v2} + L_l = t_2 * (V_2)$ (Equation 6.5)

…

$L_{vi} + L_l = t_i * (V_i)$ (Equation 6.6)

Therefore:

$$\overline{L_v} + L_l = \frac{\sum t_i * V_i}{n} \quad \text{(Equation 6.7)}$$

If $V_1 = V_2 = V_3 = \ldots = V_i = \overline{V}$, then

$$\overline{L_v} + L_l = \frac{\overline{V} * \sum t_i}{n} \quad \text{(Equation 6.8)}$$

By dividing each the top and the bottom of the fraction by time period (T), we obtain:

$$\overline{L_v} + L_l = \frac{\overline{V} * \sum \left(\frac{t_i}{T}\right)}{\frac{n}{T}} \quad \text{(Equation 6.9)}$$

$$\overline{L_v} + L_l = \frac{\overline{V} * O_T}{q_T} \quad \text{(Equation 6.10)}$$

According to Turochy and Smith (13), AEVL is the sum of the vehicle length as observed by the detectors and detector length. Therefore:

$$AEVL = \frac{\overline{V} * O_T}{q_T} \quad \text{(Equation 6.11)}$$

To explore the sensitivity of Equation 6.11 to varying speeds we need to compare:

$\frac{\sum t_i * V_i}{n}$ (from Equation 6.7) with $\frac{\overline{V} * \sum t_i}{n}$ (from Equation 6.8)

From Equation 6.7:

$$\frac{\sum t_i * V_i}{n} = \frac{t_1 * V_1 + t_2 * V_2 + ... + t_i * V_i}{n} \quad \text{(Equation 6.12)}$$

$$\frac{\sum t_i * V_i}{n} = \frac{t_1 * (\bar{V} + \Delta V_1) + t_2 * (\bar{V} + \Delta V_2) + ... + t_i * (\bar{V} + \Delta V_i)}{n} \quad \text{(Equation 6.13)}$$

Where: ΔV_i is the difference between $\bar{V}$ and the actual speed data value.

Moreover,

$$\frac{\sum t_i * V_i}{n} = \frac{\bar{V} * (t_1 + t_2 + ... + t_i) + (t_1 * \Delta V_1 + t_2 * \Delta V_2 + ... + t_i * \Delta V_i)}{n} \quad \text{(Equation 6.14)}$$

Finally,

$$\frac{\sum t_i * V_i}{n} = \frac{\bar{V} * \sum t_i + \sum (t_i * \Delta V_i)}{n} \quad \text{(Equation 6.15)}$$

Comparing $\frac{\bar{V} * \sum t_i + \sum (t_i * \Delta V_i)}{n}$ (Equation 6.15) with $\frac{\bar{V} * \sum t_i}{n}$ (Equation 6.8):

The difference in the assumption is the second term $\frac{\sum t_i \Delta V_i}{n}$.

Therefore, if $\sum t_i \Delta V_i$ is relatively small compared with $\bar{V} * \sum t_i$, then $\sum t_i \Delta V_i$ can be neglected.

By dividing $\frac{\bar{V} * \sum t_i + \sum (t_i * \Delta V_i)}{n}$ by $\frac{\bar{V} * \sum t_i}{n}$, we obtain:

$$\frac{\frac{\bar{V} * \sum t_i + \sum (t_i * \Delta V_i)}{n}}{\frac{\bar{V} * \sum t_i}{n}} = \frac{\bar{V} * \sum t_i + \sum (t_i * \Delta V_i)}{\bar{V} * \sum t_i} = \quad \text{(Equation 6.16)}$$

$$\frac{\bar{V} * \sum t_i + \sum (t_i * \Delta V_i)}{\bar{V} * \sum t_i} = 1 + \frac{\sum (t_i * \Delta V_i)}{\bar{V} * \sum t_i} \qquad \text{(Equation 6.17)}$$

By substituting t_i with $\frac{S_i}{V_i}$ we have:

$$\frac{\bar{V} * \sum t_i + \sum (t_i * \Delta V_i)}{\bar{V} * \sum t_i} = 1 + \frac{\sum (\frac{S_i}{V_i} * \Delta V_i)}{\bar{V} * \sum \frac{S_i}{V_i}} \qquad \text{(Equation 6.18)}$$

And finally,

$$\frac{\bar{V} * \sum t_i + \sum (t_i * \Delta V_i)}{\bar{V} * \sum t_i} = 1 + \frac{\sum (\frac{\Delta V_i}{V_i} * S_i)}{\bar{V} * \sum (\frac{1}{V_i} * S_i)} \qquad \text{(Equation 6.19)}$$

From the equation above, we can see that if the length S_i is constant, the ratio $\frac{\Delta V_i}{V_i}$ is the factor that affects AEVL. However, this ratio affects AEVL in relation with vehicle speeds Vi.

To examine the sensitivity of AEVL to the ratio $\frac{\Delta V_i}{V_i}$, the percentage of error in AEVL for different values of Vi (Vi = 1, 5 and 10 mph) must be assessed. Figure 6-11 depicts the error percentage in AEVL due to changes in $\frac{\Delta V_i}{V_i}$ and V_i. Note that for speeds lower than 30 mph the percentage of error in AEVL is considerably high.

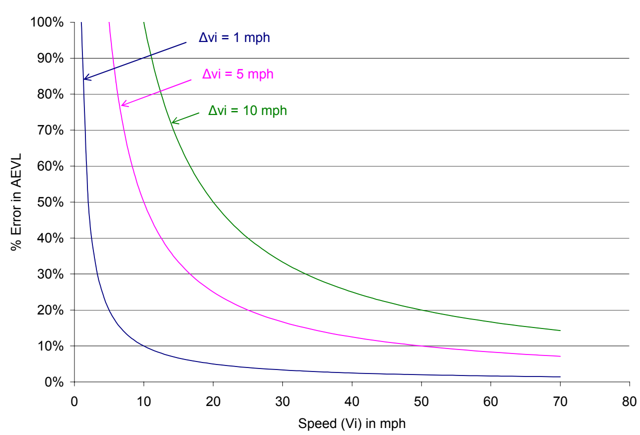


Figure 6-11: Percentage of error in AEVL, due to changes in $\frac{\Delta V_i}{V_i}$ and Vi

To illustrate this, the following example is presented (Table 6-1). Suppose we have 9 different vehicles passing over a 6x6 loop detector (row 1). The speed (V_i) and the length (L_{vi}) of each vehicle are known and, together with the length of the loop (L_l), are shown in rows 2 to 5. To calculate the time that a detector is "ON" (t_i: row 6) the following formula is used:

$$t_i = \frac{L_{Vi} + L_l}{V_i} \quad \text{(Equation 6.20)}$$

Rows	Parameters	Vehicle Characteristics								
1	Vehicle ID	1	2	3	4	5	6	7	8	9
2	V_i (mph)	70	50	60	2	3	10	15	40	55
3	V_i (ft/sec)	103	73	88	3	4	15	22	59	81
4	Veh. L_{Vi} (ft)	40	50	25	25	30	7	40	48	27
5	Loop L_l (ft)	6	6	6	6	6	6	6	6	6
6	t_i (sec)	0.45	0.76	0.35	10.57	8.18	0.89	2.09	0.92	0.41

Table 6-1: Calculation of the time the detector is "ON" for each vehicle

From the estimated time t_i, we can calculate occupancy for several combinations of vehicles (rows 1 and 2, Table 6-2), for a 30-second period. The formula used for the occupancy calculation (row 3) was:

$$O = \frac{\sum \text{Time "On" } (t_i)}{\text{Total time period}} \quad \text{(Equation 6.21)}$$

Then, the hourly equivalent volume (q) was estimated by converting the number of vehicles from 30-second intervals to 1-hour (row 4):

$$q = \frac{\text{number of vehicles} * 3600}{30} \quad \text{(Equation 6.22)}$$

Moreover, the average speed was calculated (row 5) and converted to km/h (row 6) by using the formula:

$$V \text{ (km/h)} = V \text{ (mph)} / 1.60934 \quad \text{(Equation 6.23)}$$

Then, AEVL was calculated (row 7) by using equation 5.1.

To verify the AEVL results, the "real" average length of each vehicle combination, $\overline{L_v}$ (true), was calculated in row 8 depending on the different combinations of vehicles.
For example, for the combination of vehicles 1, 2 and 3 the "real" average length for this combination was:

$$\overline{L_v}\text{ (true) (ft)} = (40 + 50 + 25) / 3 = 38.3\text{ ft}$$

Afterwards, $\overline{L_v}$ (true) was converted to meters and added to the length of the detector zone. The results are shown in raw 9 ($\overline{L_v} + L_l$ (true)) and are then compared to the results found in raw 7. Row 10, shows the difference between the results of the AEVL test (raw 7) and the results of $\overline{L_v} + L_l$ (true) (raw 9).

1	Vehicles	1	1,2	1,2,3	1,2,3,4	1,2,3,4,5	1,2,3,4,5,6	1,2,3,4,5,6,7	1,2,3,4,5,6,7,8	1,2,3,6,7,8	1,2,3,8	3	3,9
2	Volume	1	2	3	4	5	6	7	8	6	4	1	2
3	O_T (%)	1.5	4.0	5.2	40.4	67.7	70.7	77.6	80.7	18.2	8.3	1.2	2.5
4	q (veh/hr/l)	120	240	360	480	600	720	840	960	720	480	120	240
5	$\overline{V}$ (mph)	70	60	60	46	37	33	30	31	41	55	60	57.5
6	$\overline{V}$ (km/h)	113	97	97	73	60	52	48	50	66	89	97	93
7	AEVL (m)	14.0	16.3	14.0	61.7	67.2	51.3	44.6	42.3	16.6	15.3	9.4	9.8
8	$\overline{L_v}$ (true) (ft)	40	45	38	35	34	30	31	33	35	41	25	26
9	$\overline{L_v} + L_l$ (true) (m)	14.0	15.5	13.5	12.5	12.2	10.8	11.3	11.9	12.5	14.2	9.4	9.8
10	Difference AEVL (m) - $\overline{L_v} + L_l$ (true)	0.0	0.8	0.5	49.2	55.0	40.5	33.3	30.4	4.1	1.1	0.0	0.0

Table 6-2: Difference between AEVL method and results from actual data

The results illustrate that when vehicle lengths and speeds are fairly uniform and occupancies have values lower than 20%, a good agreement between the AEVL method and the actual records can be achieved. However, in the case that the speeds of the vehicles are not similar and occupancy values exceed 20%, then the AEVL test fails to give good results. The cells corresponding to these cases are depicted in Table 6-2 with grey color.

6.2.3.2. Investigation of Average Effective Vehicle Length (AEVL) for rounding occupancy

Another important concern of AEVL is the way that occupancy is reported by the detectors. When occupancy is reported with no decimals, the results of the AEVL differ significantly from the results calculated with occupancy reported in one decimal. That issue is crucial for the nighttime period (00:00 - 06:00 a.m.) when there is very low traffic volume and, as a result of this, occupancies are usually rounded to zero. The following example illustrates this issue:
Suppose we have 30 identical vehicles with length (L_{vi}) = 16 ft, passing over a 6x6 loop detector. All vehicles are assumed to have the same speed (Vi = 60 mph = 88 ft/sec). The time that the detector is "ON", due to the presence of a vehicle is calculated using the equation below:

$$t_i = \frac{L_{Vi} + L_l}{V_i} \qquad \text{(Equation 6.24)}$$

In our case:

$$t_i = \frac{(16+6)\ \text{ft}}{88\ \text{ft/sec}} = 0.25\ \text{sec} \qquad \text{(Equation 6.25)}$$

Therefore, for each vehicle the detector stays "On" for 0.25 sec.
We need to check the differences in the results provided by a sensor that reports occupancy with no decimals and a sensor that reports occupancy in one or two decimal.
To illustrate this, we can calculate AEVL for the three cases, when we have i "identical" vehicles passing over the detectors in one minute (i=1,2,3,…,30)
Hourly equivalent volume can be estimated from the number of vehicles in 1-minute intervals by using the equation below:

$$q = \frac{\text{number of vehicles} * 3600}{60} \qquad \text{(Equation 6.26)}$$

1-minute occupancy can be calculated from the estimated time t_i, using the equation below:

$$O = \frac{\sum \text{Time "On"} (t_i)}{\text{Total time period}} \qquad \text{(Equation 6.27)}$$

AEVL can be then estimated using Equation 5.1, for occupancy reported in one, two or with no decimals. The results of this example are depicted in Figure 6-12. Note that for the case that only one vehicle passed over the detector, AEVL result when occupancy is reported with no decimals was zero, where as the AEVL result when occupancy is reported in two decimals was 6.7 m.

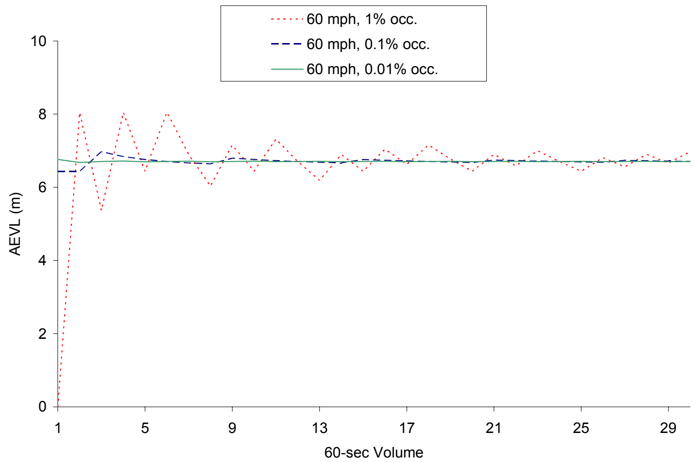


Figure 6-12: AEVL differences for occupancy reported in different decimals (V=60 mph)

The same test was applied again, for same vehicles with different speed (Vi = 30 mph = 44 ft/sec) The results of this test are depicted in Figure 6-13:

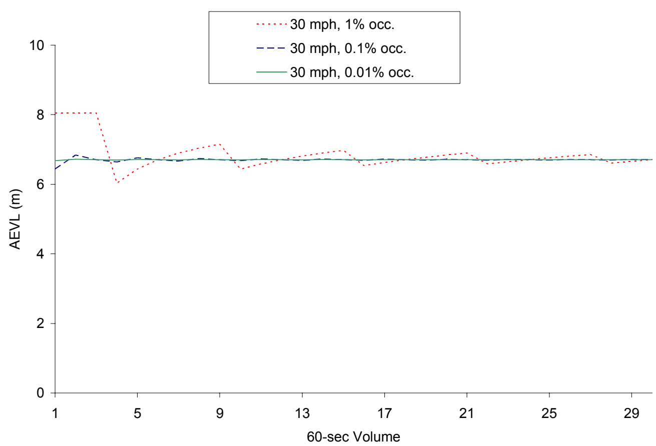


Figure 6-13: AEVL differences for occupancy reported in different decimals (V=30 mph)

Both examples illustrate that there are noticeable differences in the results of the AEVL test depending whether occupancy is reported with no decimals, in one or in two decimals, especially for the higher speeds. Particularly, for the case that only one fast vehicle passes over the detectors in a 1-minute period, occupancy with no decimals is rounded to zero and AEVL results zero, as well. On the other hand, when occupancy is reported in one or two decimals, there is little variation in the AEVL measurement.

6.2.3.3. Interpretation of the results of AEVL tests on I-465

A summary of the results for the AEVL test performed on I-465 is depicted in Table 6-3, Table 6-4 and Table 6-5.

Table 6-3 summarizes the results of AEVL test for data collected in different dates and by different detection technologies for the time period 7:00 a.m. - 3:00 p.m. Data is considered within tolerance if they are between the minimum and maximum acceptable values for AEVL which are 2.7 m (9 ft) and 18 m (60 ft), respectively. From the results shown in the table, lanes 2 and 3 seem to provide better results for AEVL than lane 1. That can be explained by the fact that in lane 1, vehicles are more likely to travel at higher speeds and as a result the average AEVL values for this lane are lower than the other lanes. However, this may cause numerous records to fall below the minimum acceptable limit of 2.7m as shown in column “percentage of values below 2.7m”. In addition, vehicles are more likely to change lanes (from lane 2 to lane 3) in order to overtake other vehicles, causing additional problems.

Table 6-4 summarizes the results of AEVL test for data collected in different dates and by different detection technologies for the morning 3-hour-period 7:00 a.m. - 10:00 a.m. and Table 6-5 summarizes the results of AEVL test for the evening 3-hour-period 7:00 a.m. - 10:00 p.m. There are not significant differences in the interpretation of the results comparing to those mentioned above for the time period 7:00 a.m. - 3:00 p.m. However, it can be noted that in both cases, AEVL test for data collected on July 22-23, 2004 (when RTMS was configured to correct occupancy measurements to be equivalent to 6-foot loop data) provided the most accurate results and a higher average AEVL value.

All the results of AEVL test for RTMS and microloops are analytically presented in the following figures:

- Figure 6-14 and Figure 6-15 depict the results of the AEVL test on July 13-14, 2004 (left column) and on July 22-23, 2004 (right column), for RTMS
- Figure 6-16 and Figure 6-17 depict the results of the AEVL test on July 1-2, 2004 (left column) and on July 9-10, 2004 (right column), for RTMS
- Figure 6-18 and Figure 6-19 depict the results of the AEVL test on July 1-2, 2004 (left column) and on July 9-10, 2004 (right column), for microloops.
- Figure 6-20 depict the results of the AEVL test on June 14-15, 2004, for RTMS

It can be denoted that AEVL tests did not reveal any significant inconsistencies except during nighttime, and particularly at very low or zero volumes and occupancies.

Lane	Sensor	Date	Time Period	% AEVL within tolerance	% of values >18m	% of values <2.7m	Aver. AEVL value (m)
1	RTMS Ser.	7/2/04	07:00 – 15:00	87.7	0.4	11.9	3.8
1	Canoga	7/2/04	07:00 – 15:00	98.8	0	1.2	4.1
1	RTMS Ser.	7/10/04	07:00 – 15:00	78.5	1.7	19.8	4.2
1	Canoga	7/10/04	07:00 – 15:00	90.8	0	9.2	4.1
1	RTMS Ser.	7/14/04	07:00 – 15:00	82.7	0	17.3	3.7
2	RTMS Ser.	7/2/04	07:00 – 15:00	100	0	0	6.2
2	Canoga	7/2/04	07:00 – 15:00	100	0	0	6.0
2	RTMS Ser.	7/10/04	07:00 – 15:00	99.4	0	0.6	5.4
2	Canoga	7/10/04	07:00 – 15:00	100	0	0	5.1
2	RTMS Ser.	7/14/04	07:00 – 15:00	100	0	0	6.4
3	RTMS Ser.	7/2/04	07:00 – 15:00	99.8	0	0.2	4.7
3	Canoga	7/2/04	07:00 – 15:00	100	0	0	6.7
3	RTMS Ser.	7/10/04	07:00 – 15:00	94.4	0	5.6	4.0
3	Canoga	7/10/04	07:00 – 15:00	100	0	0	5.4
3	RTMS Ser.	7/14/04	07:00 – 15:00	100	0	0	4.8

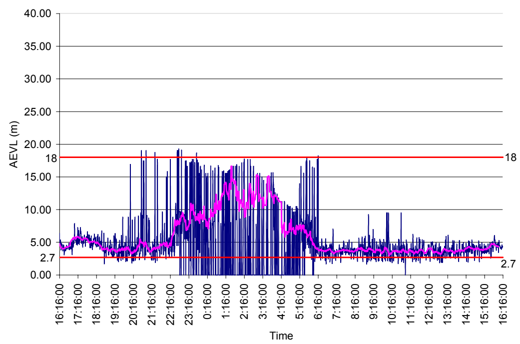
Table 6-3: Percentage of samples between upper and lower bound between 07:00 – 15:00 at I-465 at EB M.P. 36.2

Lane	Sensor	Date	Time Period	% AEVL within tolerance	% of values >18m	% of values <2.7m	Aver. AEVL value (m)
1	Canoga	7/2/04	07:00 – 10:00	97.8	0	2.2	4.2
1	RTMS Ser.	7/2/04	07:00 – 10:00	84.4	0	15.6	3.9
1	Canoga	7/10/04	07:00 – 10:00	82.2	0	17.8	4.1
1	RTMS Ser.	7/10/04	07:00 – 10:00	80.6	4.4	15.0	4.7
1	RTMS Ser.	7/14/04	07:00 – 10:00	85.0	0	15.0	3.9
1	RTMS Ser.	7/23/04	07:00 – 10:00	100	0	0	7.9
2	Canoga	7/2/04	07:00 – 10:00	100	0	0	6.2
2	RTMS Ser.	7/2/04	07:00 – 10:00	100	0	0	6.4
2	Canoga	7/10/04	07:00 – 10:00	100	0	0	5.1
2	RTMS Ser.	7/10/04	07:00 – 10:00	98.3	0	1.7	5.4
2	RTMS Ser.	7/14/04	07:00 – 10:00	100	0	0	6.1
2	RTMS Ser.	7/23/04	07:00 – 10:00	100	0	0	10.1
3	Canoga	7/2/04	07:00 – 10:00	100	0	0	6.9
3	RTMS Ser.	7/2/04	07:00 – 10:00	99.4	0	0.6	4.9
3	Canoga	7/10/04	07:00 – 10:00	100	0	0	5.6
3	RTMS Ser.	7/10/04	07:00 – 10:00	91.7	0	8.3	4.1
3	RTMS Ser.	7/14/04	07:00 – 10:00	100	0	0	4.6
3	RTMS Ser.	7/23/04	07:00 – 10:00	100	0	0	8.0

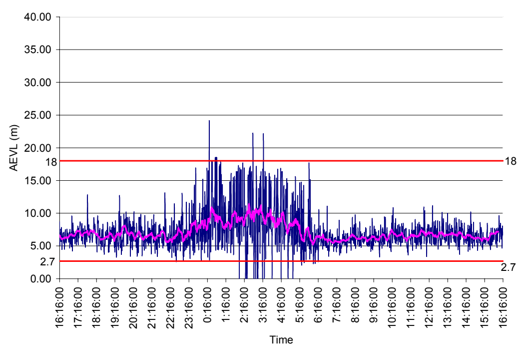
Table 6-4: Percentage of samples between upper and lower bound between 07:00 – 10:00 a.m. at I-465 at EB M.P. 36.2

Lane	Sensor	Date	Time Period	% AEVL within tolerance	% of values >18m	% of values <2.7m	Aver. AEVL value (m)
1	Canoga	7/1/04	19:00 - 22:00	86.1	0	13.9	3.8
1	RTMS Ser.	7/1/04	19:00 - 22:00	82.8	2.2	15.0	4.6
1	Canoga	7/9/04	19:00 - 22:00	86.1	0	13.9	4.0
1	RTMS Ser.	7/9/04	19:00 - 22:00	83.4	4.4	12.2	5.0
1	RTMS Ser.	7/13/04	19:00 - 22:00	83.9	1.7	14.4	4.9
1	RTMS Ser.	7/22/04	19:00 - 22:00	100	0	0	8.0
2	Canoga	7/1/04	19:00 - 22:00	100	0	0	5.7
2	RTMS Ser.	7/1/04	19:00 - 22:00	100	0	0	6.1
2	Canoga	7/9/04	19:00 - 22:00	100	0	0	5.1
2	RTMS Ser.	7/9/04	19:00 - 22:00	99.4	0	0.6	5.8
2	RTMS Ser.	7/13/04	19:00 - 22:00	100	0	0	6.7
2	RTMS Ser.	7/22/04	19:00 - 22:00	99.4	0.6	0	10.5
3	Canoga	7/1/04	19:00 - 22:00	100	0	0	5.9
3	RTMS Ser.	7/1/04	19:00 - 22:00	97.2	0	2.8	4.5
3	Canoga	7/9/04	19:00 - 22:00	100	0	0	5.2
3	RTMS Ser.	7/9/04	19:00 - 22:00	96.1	0	3.9	4.4
3	RTMS Ser.	7/19/04	19:00 - 22:00	98.3	0	1.7	4.8
3	RTMS Ser.	7/22/04	19:00 - 22:00	100	0	0	8.5

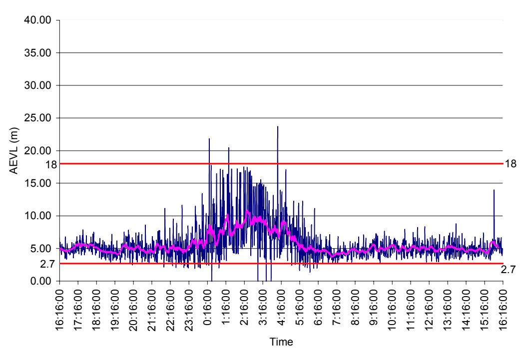
Table 6-5: Percentage of samples between upper and lower bound between 7:00 - 10:00 p.m. at I-465 at EB M.P. 36.2



a) Lane 1

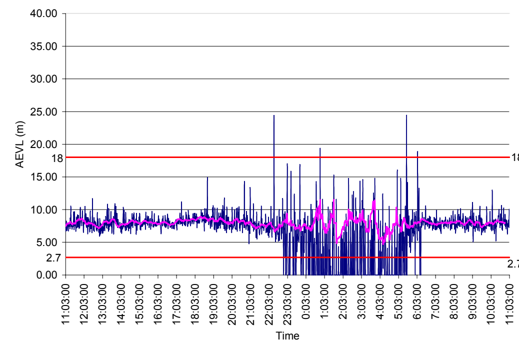


b) Lane 2

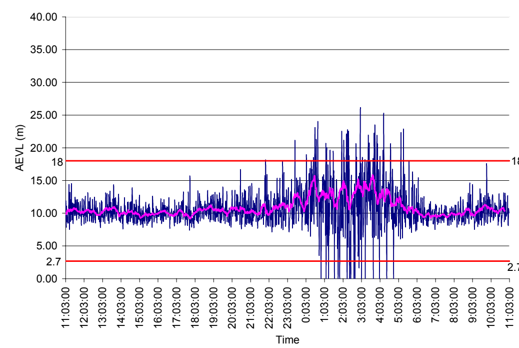


c) Lane 3

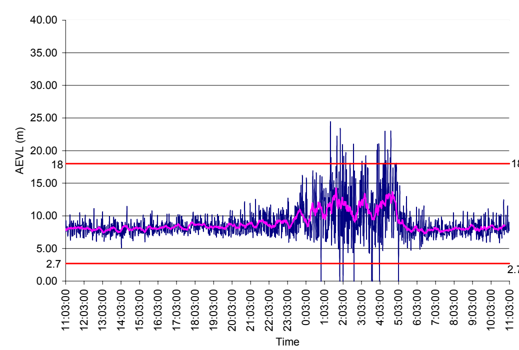
Figure 6-14: AEVL test for RTMS Serial on I-465 at M.P. 36.2 on July 13-14, 2004



a) Lane 1

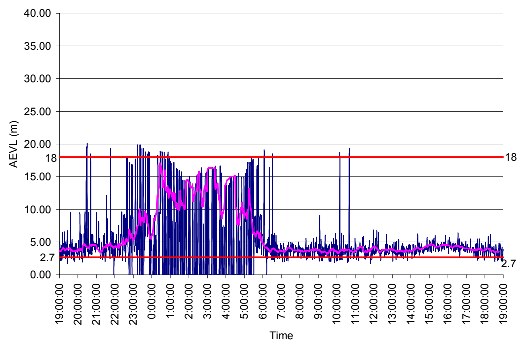


b) Lane 2

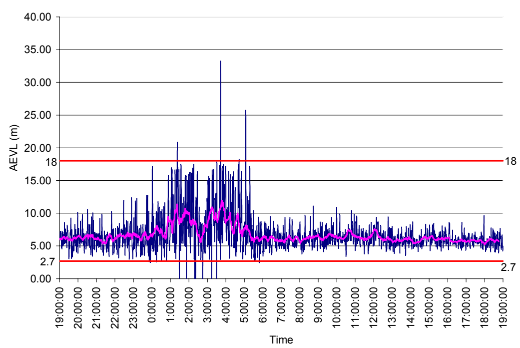


c) Lane 3

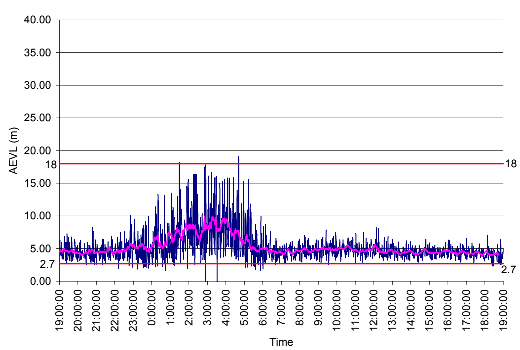
Figure 6-15: AEVL test for RTMS Serial (6 ft loop emulation) on I-465 at M.P. 36.2 on July 22-23, 2004



a) Lane 1

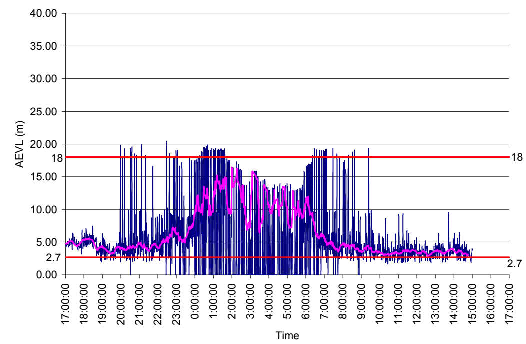


b) Lane 2

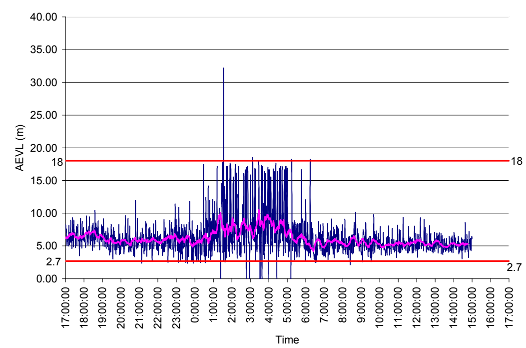


c) Lane 3

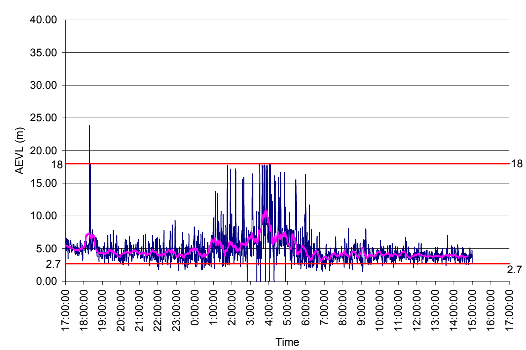
Figure 6-16: AEVL test for RTMS Serial on I-465 at M.P. 36.2 on July 1-2, 2004



a) Lane 1

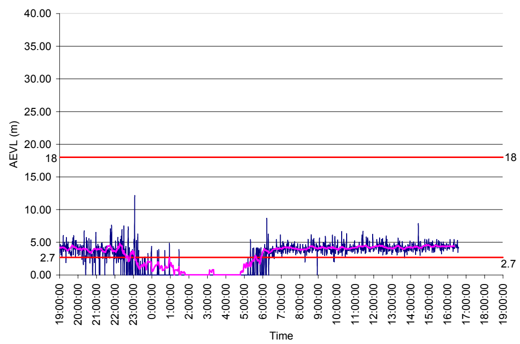


b) Lane 2

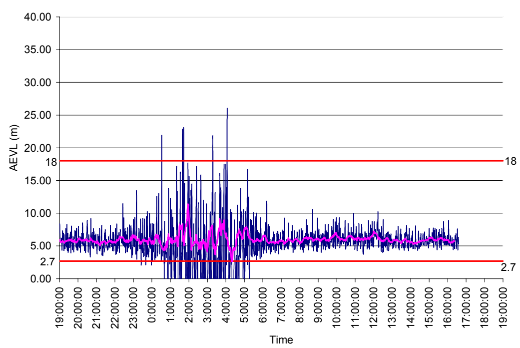


c) Lane 3

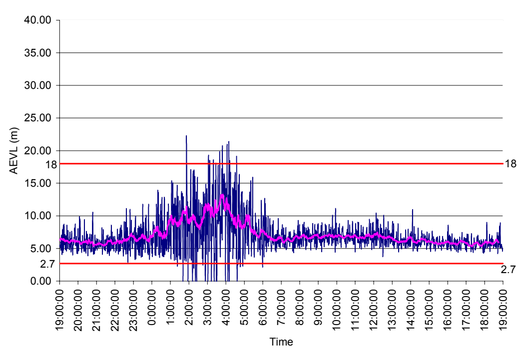
Figure 6-17: AEVL test for RTMS Serial on I-465 at M.P. 36.2 on July 9-10, 2004



a) Lane 1

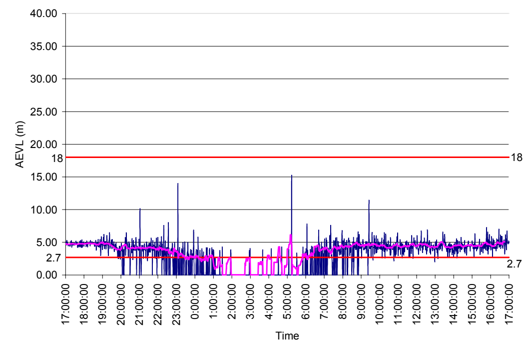


b) Lane 2

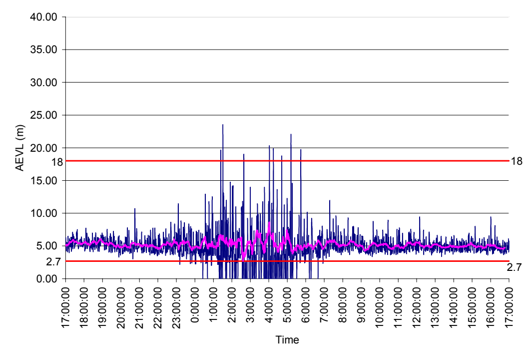


c) Lane 3

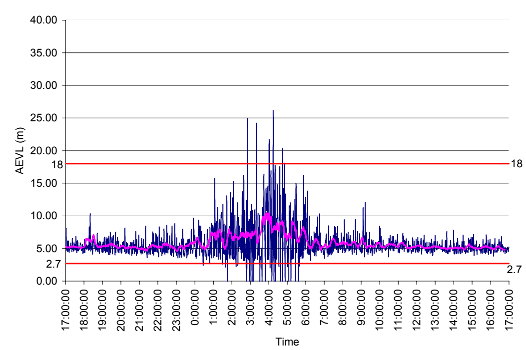
Figure 6-18: AEVL test for Microloop Canoga on I-465 at M.P. 36.2 on July 1-2, 2004



a) Lane 1

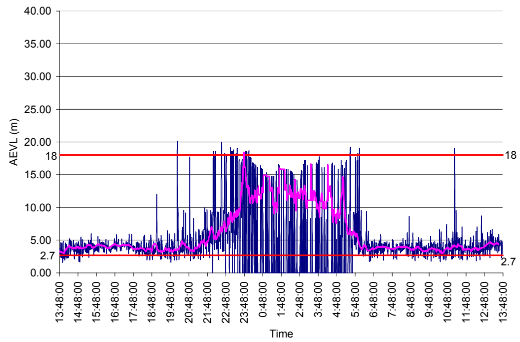


b) Lane 2

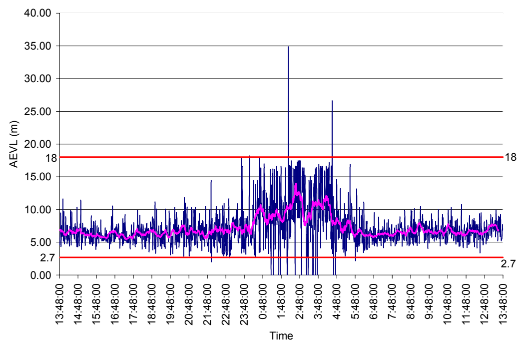


c) Lane 3

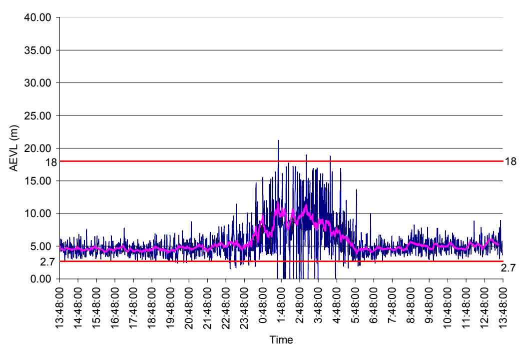
Figure 6-19: AEVL test for Microloop Canoga on I-465 at M.P. 36.2 on July 9-10, 2004



a) Lane 1



b) Lane 2



c) Lane 3

Figure 6-20: AEVL test for RTMS serial on I-465 at M.P. 36.2 on June 14-15, 2004

CHAPTER 7. BORMAN DATA SET

Chapter 7 illustrates perhaps the most challenging aspect of this project; how to apply the proposed quality control procedures to a region that has deployed numerous sensors. In this chapter, the tests described in Chapters 5 and 6 are applied for the Borman Expressway, and several important issues are addressed such as flow continuity, speed consistency along the freeway and data availability.

7.1. Application of the proposed quality control procedures on data of I-80/94

7.1.1. Flow Continuity

As discussed in Chapter 5, an effective way to check whether two closely spaced detectors are working properly is by obtaining 24-hour volume graphs and then measuring the differences in the results provided by the two detectors. However, the main limitation of this test is that entering or exiting ramps should not be located between the sensors. If this limitation is not satisfied, the measured traffic volume will be significantly different for each sensor, and therefore, any volume comparisons will not be valid. Figure 7-1, depicts a candidate site for flow conservation test, as it does not have entering or exiting ramps between the detectors.

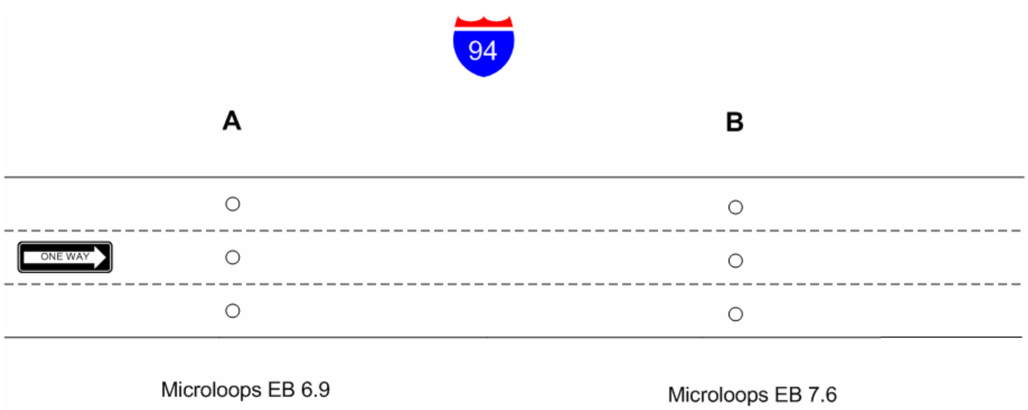
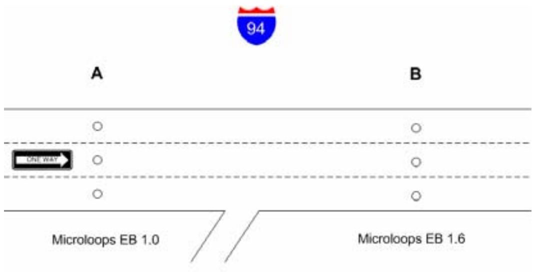
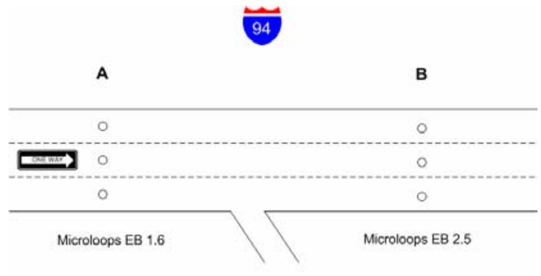


Figure 7-1: Candidate for flow conservation test (A=B)

On the contrary, Figure 7-2 depicts sites that cannot be used for the particular test because between the two sensors entering and exiting ramps are located.



a) Candidate for flow increase test (A<B)



b) Candidate for flow decrease test (A>B)

Figure 7-2: Limitations in flow conservation test

There were only 8 locations, that satisfy this limitation. For eliminating any inconsistencies due to the fact that the sensors are located approximately 0.5 miles from each other and vehicles might change lanes, the volume used in the analysis is the sum of the vehicles passing over the detectors in all three lanes. However, the generated graphs, which are analytically shown in the following figures, indicated that only 3 out of 8 locations reported consistent results.

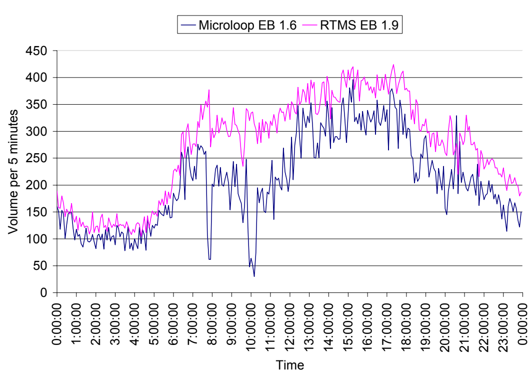


Figure 7-3 Volume comparisons for microloop at EB MP 1.6 and RTMS at EB MP 1.9 on I-80/94, on Feb 25, 2004

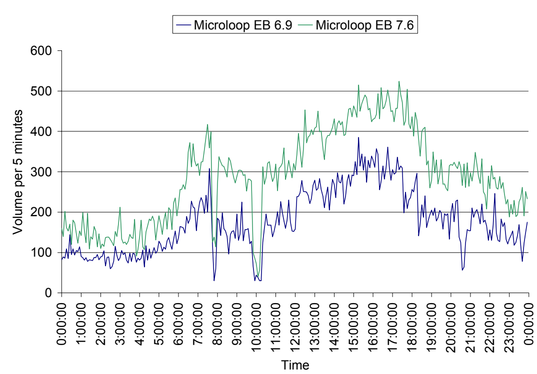


Figure 7-4: Volume comparisons for microloop at EB MP 6.9 and microloop at EB MP 7.6, on I-80/94, on Feb 25, 2004

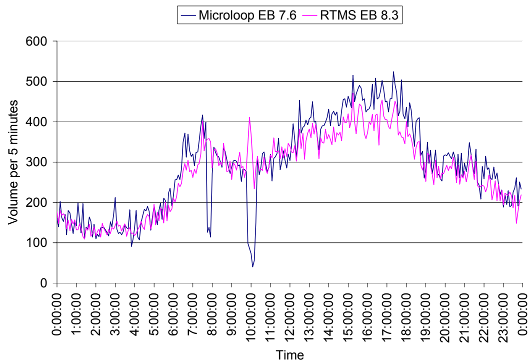


Figure 7-5: Volume comparisons for microloop at EB MP 7.6 and RTMS at EB MP 8.3 on I-80/94, on Feb 25, 2004

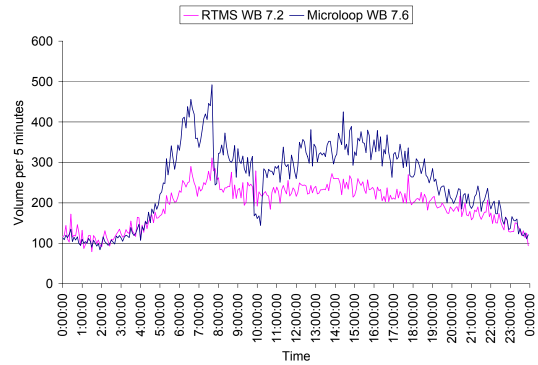


Figure 7-8: Volume comparisons for RTMS at WB MP 7.2 and RTMS at WB MP 7.6 on I-80/94, on Feb 25, 2004

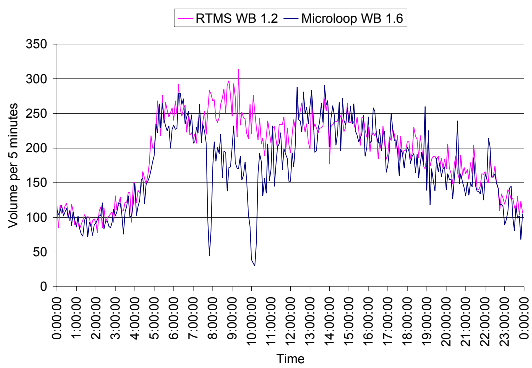


Figure 7-6: Volume comparisons for RTMS at WB MP 1.2 and microloop at WB MP 1.6 on I-80/94, on Feb 25, 2004

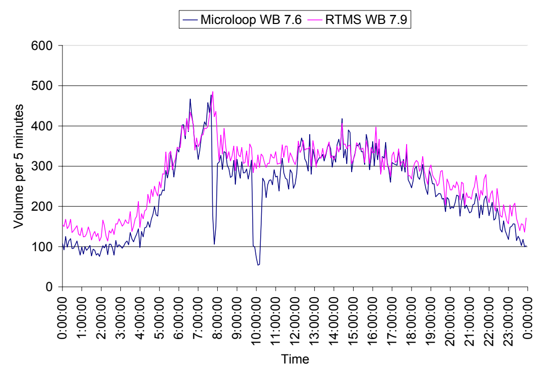


Figure 7-9: Volume comparisons for microloop at WB MP 7.6 and RTMS at WB MP 7.9 on I-80/94, on Feb 25, 2004

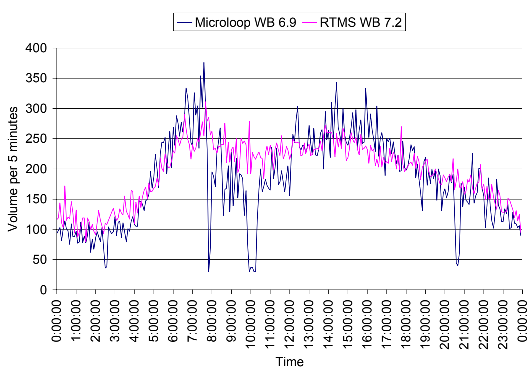


Figure 7-7: Volume comparisons for microloop at WB MP 6.9 and RTMS at WB MP 7.2 on I-80/94, on Feb 25, 2004

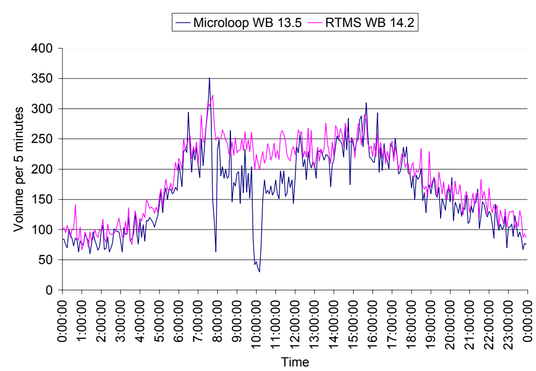


Figure 7-10: Volume comparisons for microloop at WB MP 13.5 and RTMS at WB MP 14.2 on I-80/94, on Feb 25, 2004

Table 7-1, summarizes the results of the flow conservation test and depicts the sensors that reported consistent flows.

Volume Comparisons		Consistent Flow
EB 1.6 Microloop Vs EB 1.9 RTMS	Figure 7-3	
EB 6.9 Microloop Vs EB 7.6 Microloop	Figure 7-4	
EB 7.6 Microloop Vs EB 8.3 RTMS	Figure 7-5	X
WB 1.2 RTMS Vs WB 1.6 Microloop	Figure 7-6	
WB 6.9 Microloop Vs WB 7.2 RTMS	Figure 7-7	X
WB 7.2 RTMS Vs WB 7.6 Microloop	Figure 7-8	
WB 7.6 Microloop Vs WB 7.9 RTMS	Figure 7-9	
WB 13.5 Microloop Vs WB 14.2 RTMS	Figure 7-10	X

Table 7-1: Summary of flow conservation test for volumes (all lanes) for two consecutive sites on Feb. 25, 2004 at I-80/94

7.1.2. Speed Comparisons

Similar procedure was followed for speed comparison tests. The basic limitation was the same; speed data should have been provided from two closely spaced sensors, with no entering or exiting ramps between them. However, in this case the analysis was done for each lane separately as not all the lanes were expected to provide the same magnitude of speeds. For example, a sensor in lane 3 is more likely to report higher speeds than a sensor in lane 1, which is the lane closer to the shoulder.

The graph observation (Appendix A) indicated that 6 out of 24 lanes, had reported consistent speeds over several hours. Table 7-2 summarizes the results of the speed comparison test and pinpoints the graphs in which speeds appeared consistent.

Speed Comparisons		Test Limitation	Consistent Speeds
EB 1.6 Microloop Vs EB 1.9 RTMS	Figure A-1	Lane 1	X
		Lane 2	X
		Lane 3	X
EB 6.9 Microloop Vs EB 7.6 Microloop	Figure A-2	Lane 1	
		Lane 2	X
		Lane 3	
EB 7.6 Microloop Vs EB 8.3 RTMS	Figure A-3	Lane 1	X
		Lane 2	
		Lane 3	
WB 1.2 RTMS Vs WB 1.6 Microloop	Figure A-4	Lane 1	
		Lane 2	
		Lane 3	
WB 6.9 Microloop Vs WB 7.2 RTMS	Figure A-5	Lane 1	
		Lane 2	
		Lane 3	
WB 7.2 RTMS Vs WB 7.6 Microloop	Figure A-6	Lane 1	
		Lane 2	
		Lane 3	
WB 7.6 Microloop Vs WB 7.9 RTMS	Figure A-7	Lane 1	X
		Lane 2	
		Lane 3	
WB 13.5 Microloop Vs WB 14.2 RTMS	Figure A-8	Lane 1	
		Lane 2	
		Lane 3	

Table 7-2: Summary of speed consistency for two consecutive sites on Feb. 25, 2004 at I-80/94 (graphs in Appendix A).

7.1.3. Data Availability test

In Chapter 3, data availability was defined as the degree to which data values are present in the attributes that require them [Turner, 2004]. As a result, it can be assessed by calculating the percentage of available data in data archives. Equation 7.1 illustrates how data availability can be represented as the quotient of the actual number of records or observations that exists in a data archive, divided by the total possible number of records or observations, respectively.

$$\text{Data Availability} = \frac{\text{Actual number of observations}}{\text{Expected number of records}} * 100\% \qquad \text{(Equation 7.1)}$$

For example, if data availability reported by a sensor is fifty percent, then the data considered for further statistical analysis are only half of the total data that was initially estimated to be reported by the sensor.

However, to assess data availability for all microloop detectors and RTMS sensors at I-80/94, a different test was applied for the reporting frequency of each station. The reason for this was that the data provided by these sensors are not reported in constant time intervals (e.g. every 30 seconds), and therefore the data analysis needed to be more explicit.

The first step of the procedure was to quantify the number of sample counts in each set of data for every 15-minute period. Then, the Poisson distribution (Equation 7.2) was used for estimating the probability to have no vehicle arrivals in the 15-min period, based on the measured 15-min traffic volume.

$$P(n) = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \qquad \text{(Equation 7.2)}$$

Where: P(n): probability that exactly n vehicles arrive in time interval t

t: duration of time interval

λ: arrival rate

n: number of vehicles

To use this distribution, vehicle arrivals were considered random and vehicle flow rate was assumed constant. In this way, a reasonable estimation for the number of expected vehicle counts in the dataset was provided. The final step was to calculate the differences between the actual reports and the expected values and generate graphs illustrating any discrepancies.

The following example illustrates the way data availability test was applied for actual data reported by microloops on I-80/94, eastbound approach, M.P. 6.9. This example is focused on the time period 07:45 -08:00 a.m. as shown in Figure 7-11.

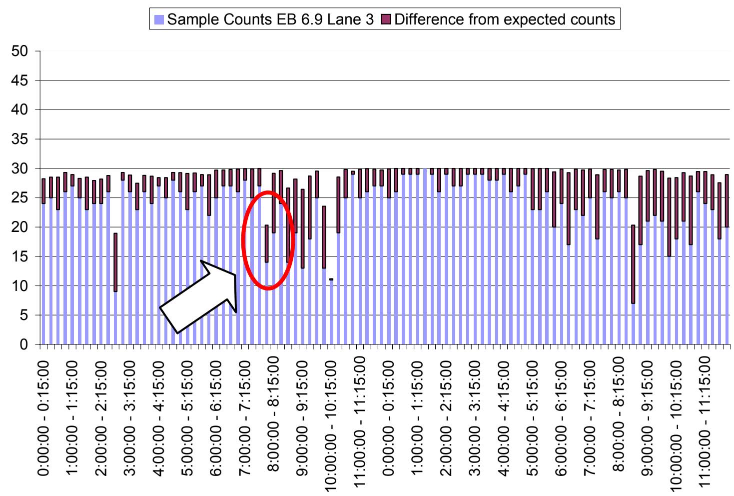


Figure 7-11: Data availability test for EB microloop, M.P. 6.9, on I-80/94

The actual data reported by the detector for the particular period are depicted in Table 7-3. Note that we wave only 14 records (normally we expect 30 records for 15-min period, or 2 records per minute) and the total 15-min volume is 34 vehicles.

Data	Time	Volume	Occupancy	Speed
1	7:45:16	3	0	62
2	7:45:45	8	0	60
3	7:47:52	1	0	67
4	7:49:11	1	0	67
5	7:50:56	1	0	71
6	7:52:10	1	0	50
7	7:52:45	1	0	109
8	7:53:52	1	0	61
9	7:54:49	1	0	61
10	7:56:09	1	0	67
11	7:57:53	1	1	101
12	7:58:39	1	0	120
13	7:59:08	5	0	71
14	7:59:40	8	2	62

Table 7-3: Actual data for the time period 07:45 - 08:00 a.m.

From the equation 7.2, the probability P(0) that no vehicle (n=0) arrives in time interval t is:

$$P(0) = e^{-\lambda t} \qquad \text{(Equation 7.3)}$$

By substituting:

Arrival rate (λ): 34 vehicles / 15 minutes = 1.13 vehicles / 30 seconds

Time interval (t): 30 seconds

The probability P(0) that no vehicle arrives in time interval equals:

P(0) = 9.66 ≈ 10 vehicles

Therefore, the expected number of counts in our sample is:

30 vehicles - 10 vehicles = 20 vehicles

However, in our sample we have only 14 records, so the difference from the expected counts is:

20 vehicles - 14 vehicles = 6 vehicles (depicted in Figure 7-11)

All the graphs concerning the data availability test are shown in Appendix B. Table 7-4 and Table 7-5 summarize the results of the data availability test for data collected on February 25, 2004. Note that all graphs revealed problems in data availability between 07:45 - 08:00 a.m and 10:00 - 10:30 a.m perhaps due to either a failure of the central traffic management system and the data archiving system or a disruption of communications between field controllers and central management system.

Site	Lane	Microloop		RTMS	
		Data Availability	Regular Data Reporting	Data Availability	Regular Data Reporting
EB 1.0	1	Figure B-1	X		
	2		X		
	3		X		
EB 1.6	1	Figure B-2			
	2				
	3				
EB 1.9	1			Figure B-3	X
	2				X
	3				X
EB 2.5	1	Figure B-4	X		
	2		X		
	3		X		
EB 3.4	1	Figure B-5	X		
	2		X		
	3		X		
EB 3.7	1			Figure B-6	X
	2				X
	3				X
EB 6.0	1			Figure B-7	X
	2				X
	3				X
EB 6.4	1	Figure B-8	X		
	2		X		
	3		X		
EB 6.9	1	Figure B-9			
	2				
	3				
EB 7.6	1	Figure B-10	X		
	2		X		
	3		X		
EB 8.3	1			Figure B-11	X
	2				X
	3				X
EB 9.5	1			Figure B-12	
	2				
	3				
EB 11.9	1	Figure B-13	X		
	2		X		
	3				
EB 12.6	1			Figure B-14	X
	2				X
	3				X
EB 13.5	1	Figure B-15	X		
	2		X		
	3		X		
EB 15.6	1	Figure B-16	X		
	2		X		
	3		X		

Table 7-4: Data availability for each lane of each eastbound sensor on I-80/94, for Feb. 25, 2004 (graphs in Appendix B).

Site	Lane	Microloop		RTMS	
		Data Availability	Regular Data	Data Availability	Regular Data
WB 0.0	1	Figure B-17	X		
	2		X		
	3		X		
WB 0.8	1	Figure B-18	X		
	2		X		
	3		X		
WB 1.2	1			Figure B-19	X
	2				X
	3				X
WB 1.6	1	Figure B-20			
	2				
	3				
WB 2.9	1			Figure B-21	X
	2				X
	3				X
WB 4.2	1	Figure B-22			
	2				
	3				
WB 6.4	1	Figure B-23	X		
	2		X		
	3				
WB 6.9	1	Figure B-24			
	2				
	3				
WB 7.2	1			Figure B-25	X
	2				
	3				
WB 7.6	1	Figure B-26	X		
	2		X		
	3		X		
WB 7.9	1			Figure B-27	X
	2				X
	3				X
WB 8.7	1	Figure B-28			
	2				
	3				
WB 11.7	1	Figure B-29	X		
	2		X		
	3		X		
WB 12.5	1	Figure B-30			
	2				
	3				
WB 13.5	1	Figure B-31	X		
	2				
	3		X		
WB 14.2	1			Figure B-32	X
	2				X
	3				X
WB 14.9	1	Figure B-33	X		
	2		X		
	3		X		

Table 7-5: Data availability for each lane of each westbound sensor on I-80/94, for Feb. 25, 2004 (graphs in Appendix B)

7.1.4. AEVL Test

This method, which was described explicitly in chapter 6, was also used for screening traffic data provided by microloops and RTMS on I-80/94. All generated graphs representing AEVL tests for I-80/94 data are shown in Appendix C. Table 7-7 and Table 7-8 summarize the results of these tests.

The results revealed significant inconsistencies in microloops AEVL tests. That is because in many records, occupancy reported by microloops was zero. An example of I-80/94 data (microloop at M.P. 1.0 eastbound approach) is depicted in Table 7-6. We can notice that in some cases, even when we had 7 or 8 vehicles during a 30-second interval the occupancy reported was zero.

Sensor's ID	Lane	Time	Volume	Occupancy	Speed
'dti94e10e'	3	6:42:14	4	1	56
'dti94e10e'	3	6:42:44	3	0	58
'dti94e10e'	3	6:43:14	3	0	59
'dti94e10e'	3	6:43:44	12	1	49
'dti94e10e'	3	6:44:14	5	0	57
'dti94e10e'	3	6:44:47	7	7	55
'dti94e10e'	3	6:45:15	8	0	56
'dti94e10e'	3	6:45:45	6	4	62
'dti94e10e'	3	6:46:15	5	0	57
'dti94e10e'	3	6:46:45	8	1	49
'dti94e10e'	3	6:47:15	6	6	47
'dti94e10e'	3	6:47:45	4	0	54
'dti94e10e'	3	6:48:15	7	1	62
'dti94e10e'	3	6:48:45	3	6	54
'dti94e10e'	3	6:49:15	5	1	57
'dti94e10e'	3	6:49:46	7	0	63

Table 7-6: Example of I-80/94 data on February 25, 2004, (Microloop EB at M.P. 1.0)

Site	Lane	Microloop		RTMS	
		AEVL Test	AEVL within expected range	AEVL Test	AEVL within expected range
EB 1.0	1	Figure C-1			
	2		X		
	3				
EB 1.6	1	Figure C-2			
	2		X		
	3				
EB 1.9	1			Figure C-11	X
	2				X
	3				X
EB 2.5	1	Figure C-3			
	2				
	3				
EB 3.4	1	Figure C-4			
	2		X		
	3				
EB 3.7	1			Figure C-12	X
	2				X
	3				X
EB 6.0	1			Figure C-13	X
	2				X
	3				X
EB 6.4	1	Figure C-5			
	2				
	3				
EB 6.9	1	Figure C-6			
	2				
	3				
EB 7.6	1	Figure C-7			
	2				
	3				
EB 8.3	1			Figure C-14	X
	2				X
	3				X
EB 9.5	1			Figure C-15	
	2				
	3				
EB 11.9	1	Figure C-8			
	2				
	3				
EB 12.6	1			Figure C-16	X
	2				X
	3				X
EB 13.5	1	Figure C-9			
	2				
	3				
EB 15.6	1	Figure C-10			
	2				
	3				

Table 7-7: AEVL Test for each lane of each eastbound sensor on I-80/94, for Feb. 25, 2004 (graphs in Appendix C).

Site	Lane	Microloop		RTMS	
		AEVL Test	AEVL within ex. range	AEVL Test	AEVL within ex. range
WB 0.0	1	Figure C-17			
	2				
	3				
WB 0.8	1	Figure C-18			
	2				
	3				
WB 1.2	1			Figure C-29	X
	2				X
	3				X
WB 1.6	1	Figure C-19			
	2				
	3				
WB 2.9	1			Figure C-30	X
	2				X
	3				X
WB 4.2	1	Figure C-20			
	2				
	3				
WB 6.4	1	Figure C-21			
	2				
	3				
WB 6.9	1	Figure C-22			
	2				
	3				
WB 7.2	1			Figure C-31	
	2				X
	3				X
WB 7.6	1	Figure C-23			
	2				
	3				
WB 7.9	1			Figure C-32	X
	2				X
	3				X
WB 8.7	1	Figure C-24			
	2				
	3				
WB 11.7	1	Figure C-25			
	2				
	3				
WB 12.5	1	Figure C-26			
	2				
	3				
WB 13.5	1	Figure C-27			
	2				
	3				
WB 14.2	1			Figure C-33	X
	2				X
	3				X
WB 14.9	1	Figure C-28			
	2				
	3				

Table 7-8: AEVL Test for each lane of each westbound sensor on I-80/94, for Feb. 25, 2004 (graphs in Appendix C).

CHAPTER 8. CONCLUSIONS

8.1. Introduction

This project has presented a quality control procedure that can be used to evaluate the performance of ITS sensors, which are deployed to freeway arterials to collect continuous traffic data. As illustrated in the previous chapters, assessing the quality of the data collected by different detection technologies is a very complicated task. There are several reasons that were addressed in this study and were found to affect data quality such as:

- Failures of the equipment
- Failures of the central traffic management system or data archiving system
- Disruption of communications between field controllers and central management system
- Improper installation or calibration of the sensors
- Lack of systematic evaluation procedures for scheduling and prioritizing maintenance

This chapter summarizes the possible metrics that will improve the quality of the traffic data and recommends improvement to ensure that data quality will be preserved at a high level for a long period of time.

8.2. Recommendations

The following recommendations are made to address the above-mentioned problems:

- Microloops and RTMS sensors co-located or at closely spaced locations to provide a mechanism for automatic and continuous quality control monitoring
- As-built diagrams should be required by the provisions to ensure sensors are installed according to vendor specifications
- Performance reports should be generated at a daily basis to assess data quality
- Occupancy captured by the detectors should be reported with at least one decimal, to eliminate possible discrepancies in data quality analysis

The implementation and usefulness of these measures are discussed more explicitly in the following paragraphs.

8.2.1. Sensors positioned at the same location or closely spaced locations

The first measure proposed in this project involves the location of the microloops or radar sensors. Currently, in the Borman Expressway, there are very few sites, having no entering or exiting ramps between them, where two detection technologies can be used together to validate traffic data. As a result, the tests regarding the continuity of flow and speed comparisons are used only in a limited area, and are insufficient to monitor the performance of sensors along the entire freeway.

This study recommends that microloops and RTMS sensors should be positioned at the same location or at closely spaced locations. Once this measure is applied, the quality of the data can be continually monitored and therefore, information that is more accurate will be provided to both operators and users. In addition, potential sensor failures will be immediately recognized, when the generated graphs appear inconsistencies.

Finally, the cost of positioning microloops and RTMS at closed spaced locations is believed to be significantly lower comparing to the benefits obtained after the implementation of this measure. The reason for that is that it will be expensive and impractical to assign labor to groundtruth manually all sensor data on a routine schedule.

8.2.2. Proposed As-built diagrams

The second recommendation is the implementation of as-built diagrams for documenting microloop in-place configuration (Figure 4-10, Table 4-1) and radar device installation (Figure 4-12, Table 4-2), and as-built waveforms for assessing microloops performance. This measure will be very easy to be applied and will lead to a tighter construction tolerance. As it was discussed in previous chapters, as-built diagrams are useful because they provide information about dimensions (depths, widths, offsets, spacing) and descriptions of any subsurface infrastructure.

Another benefit is the fact that agency's personnel will be aware of any unusual patterns in infrastructure and, as a result, important time will be saved during any maintenance activities

8.2.3. Performance Reports

The current project identified various metrics to assess the quality of the traffic data. The most important metrics to evaluate the performance of microloop and radar detection technologies were the following:

1. Volume comparisons
2. Speed comparisons
3. Data availability
4. Average Effective Vehicle Length (AEVL) test

Several benefits can be obtained by the implementation of these metrics:

- Any inconsistencies in data generated by the detectors will be easily captured
- Any problems that affect the performance of the detectors will be revealed
- Traffic situations under congestion will be represented
- Possible incidents that reduce the capacity of the freeway will be detected
- Traffic data can be archived and used for future transportation planning purposes

8.2.4. Occupancy Reporting

The last measure proposed in this study is related to the way traffic data is reported in the log-files. As it was illustrated in Chapter 6, when occupancy is reported in one or more decimals, the results of the AEVL test are more accurate compared to the results of the same test with occupancy reported with no decimals. This fact is very significant particularly in capturing low-traffic situations especially during nighttime periods. This measure is very easy to be implemented as both microloop and RTMS technologies give the operator the option to capture occupancy in a more specific way, with one or two decimals.

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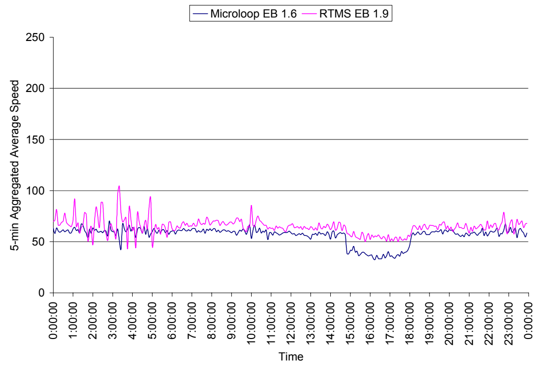
Appendix A. Speed Comparisons



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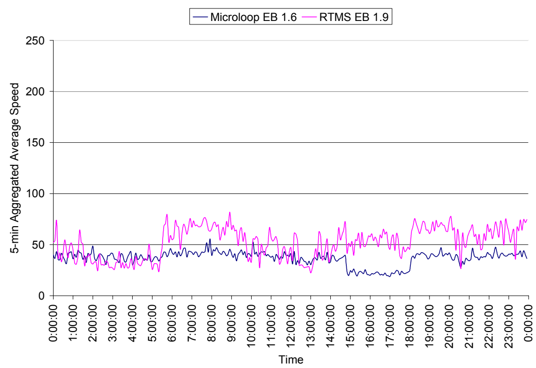

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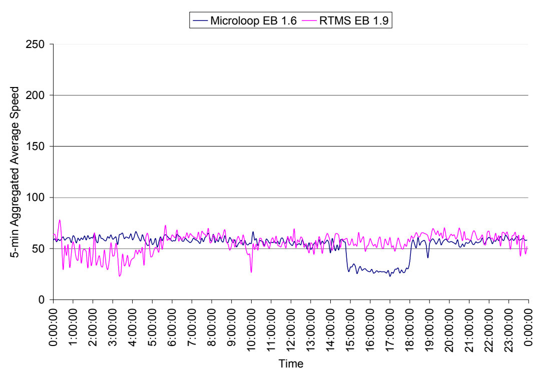
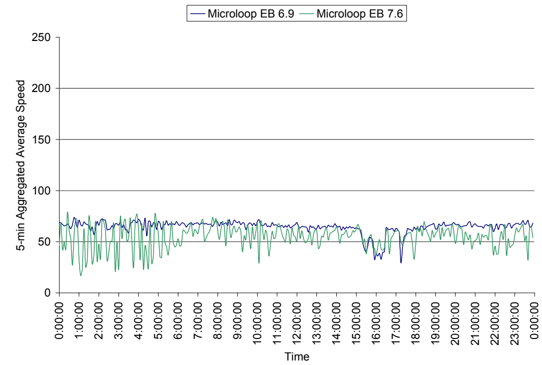


c) Lane 3

Figure A-1: Speed comparisons for microloop at EB MP 1.6 and RTMS at EB MP 1.9 on I-80/94, on Feb 25, 2004



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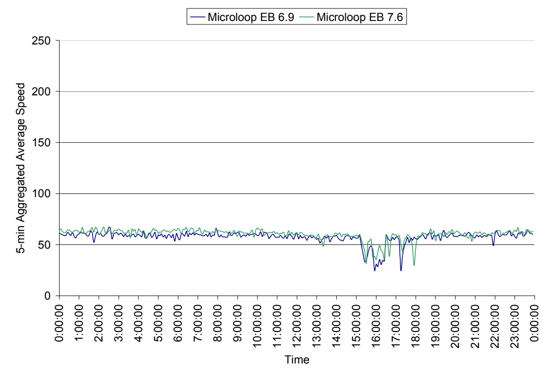

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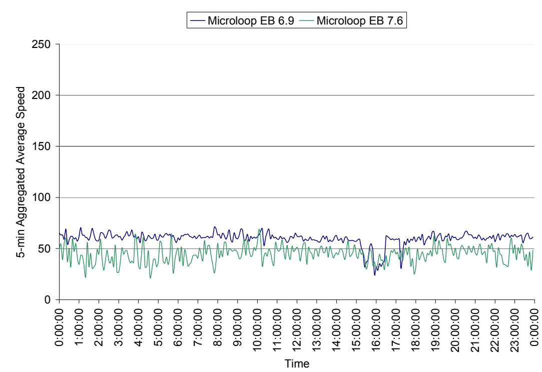
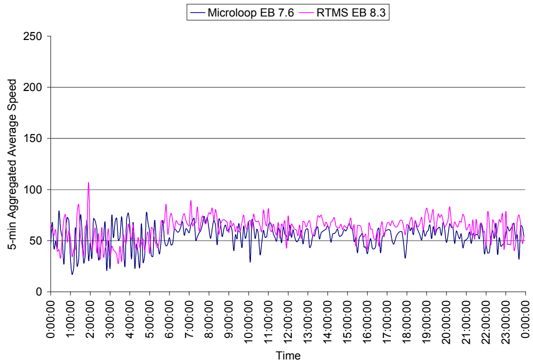


c) Lane 3

Figure A-2: Speed comparisons for microloop at EB MP 6.9 and microloop at EB MP 7.6, on I-80/94, on Feb 25, 2004



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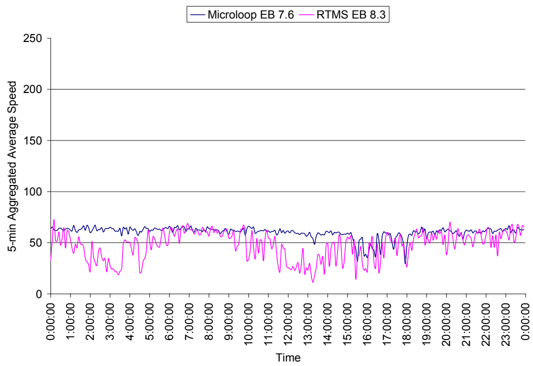

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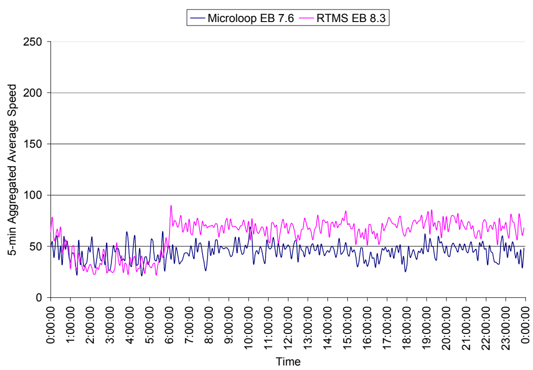
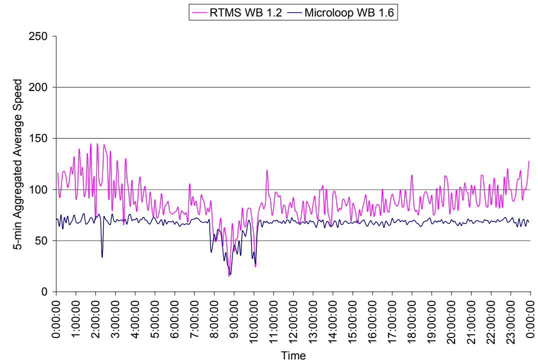


c) Lane 3

Figure A-3: Speed comparisons for microloop at EB MP 7.6 and RTMS at EB MP 8.3 on I-80/94, on Feb 25, 2004



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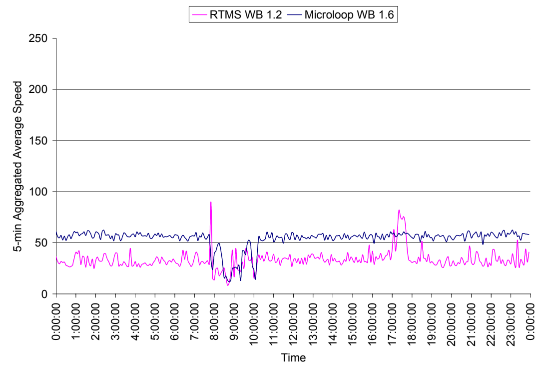

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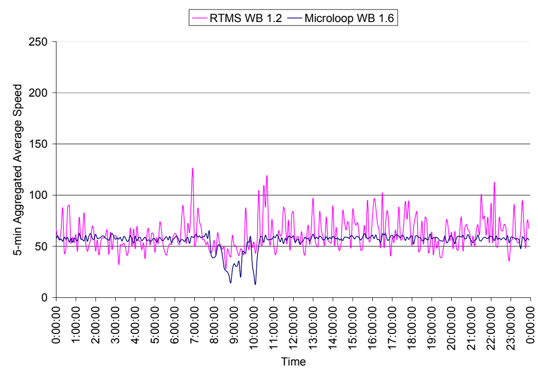
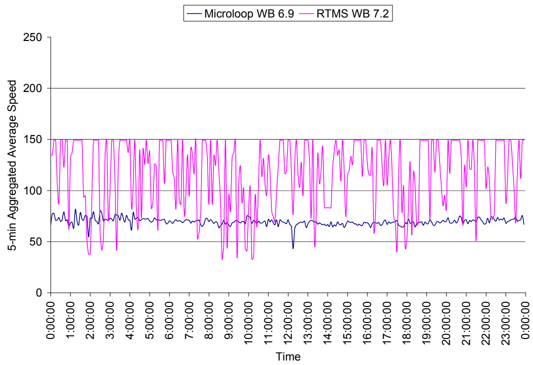


c) Lane 3

Figure A-4: Speed comparisons for RTMS at WB MP 1.2 and microloop at WB MP 1.6 on I-80/94, on Feb 25, 2004



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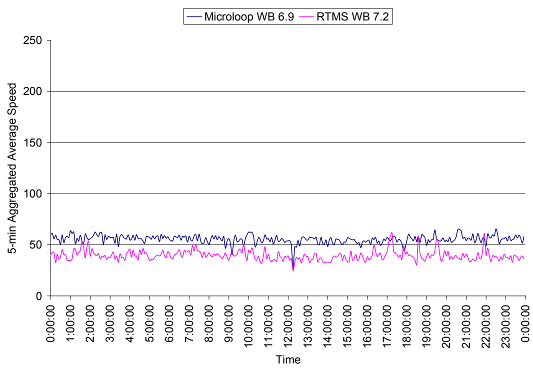

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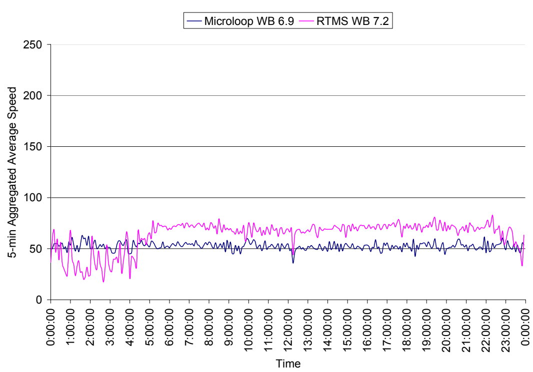

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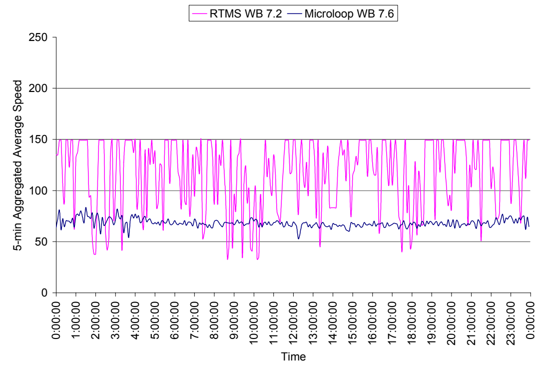
Figure A-5: Speed comparisons for microloop at WB MP 6.9 and RTMS at WB MP 7.2 on I-80/94, on Feb 25, 2004



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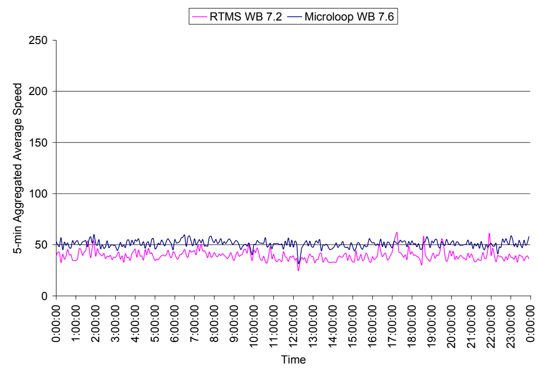

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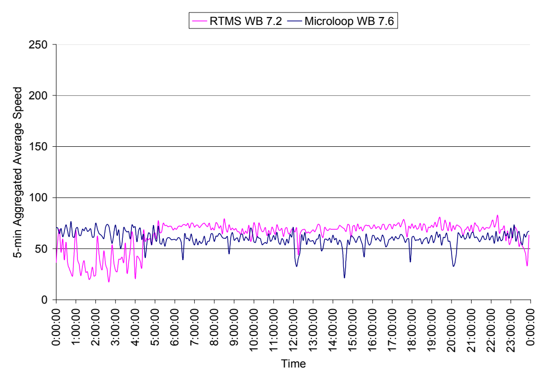

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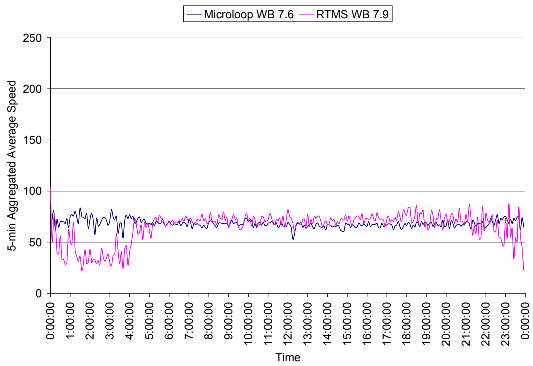
Figure A-6: Speed comparisons for RTMS at WB MP 7.2 and RTMS at WB MP 7.6 on I-80/94, on Feb 25, 2004



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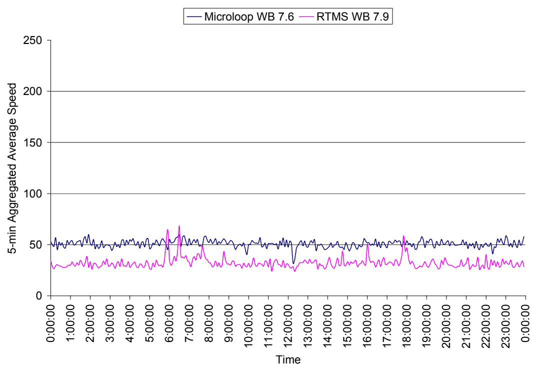

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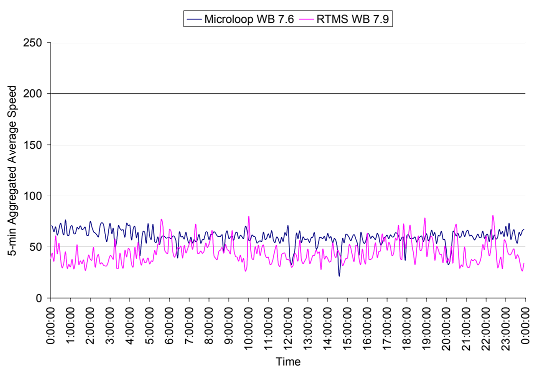

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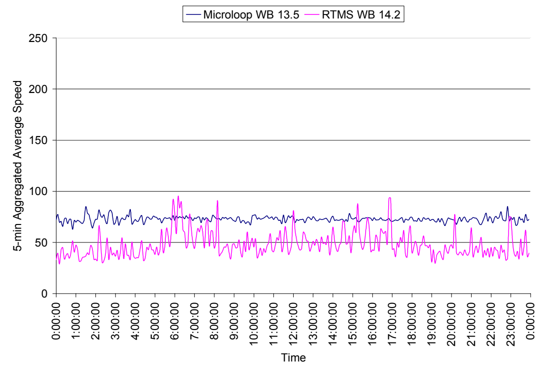
Figure A-7: Speed comparisons for microloop at WB MP 7.6 and RTMS at WB MP 7.9 on I-80/94, on Feb 25, 2004



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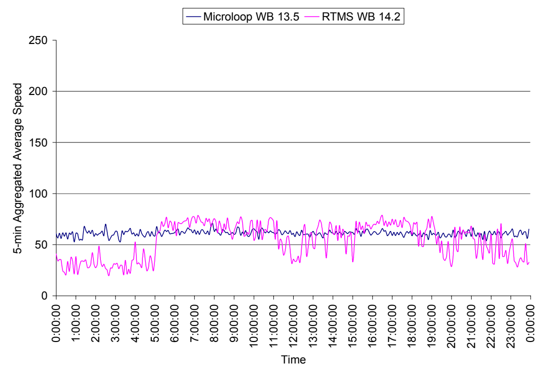

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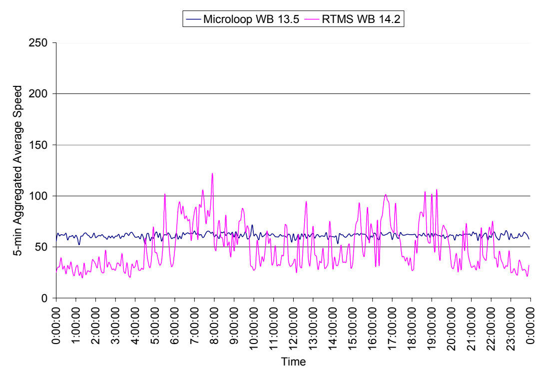
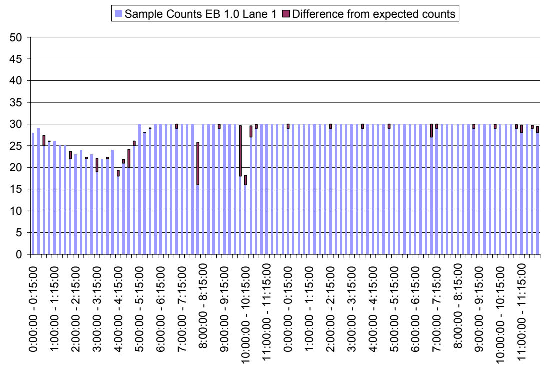


c) Lane 3

Figure A-8: Speed comparisons for microloop at WB MP 13.5 and RTMS at WB MP 14.2 on I-80/94, on Feb 25, 2004

Appendix B. Data Availability



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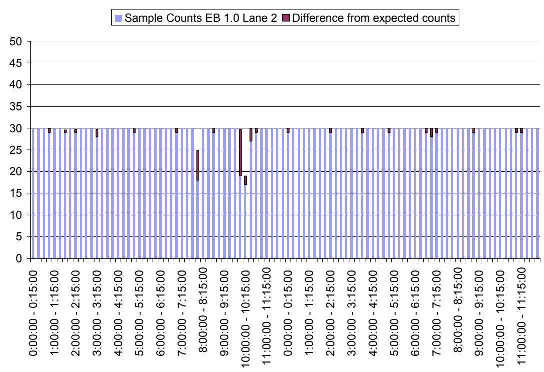

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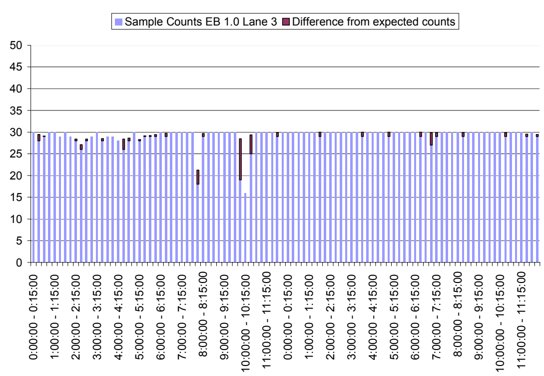
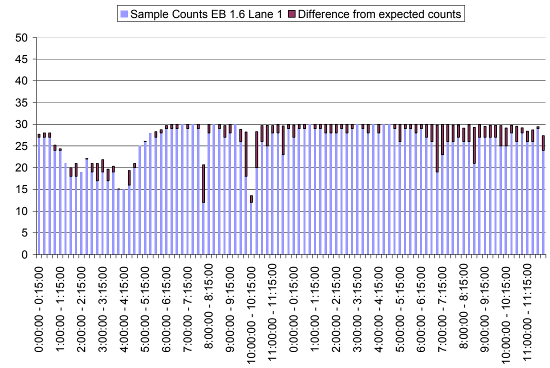


c) Lane 3

Figure B-1: Sample counts and differences from expected counts for microloop on I-80/94, at EB MP 1.0, on Feb. 25, 2004



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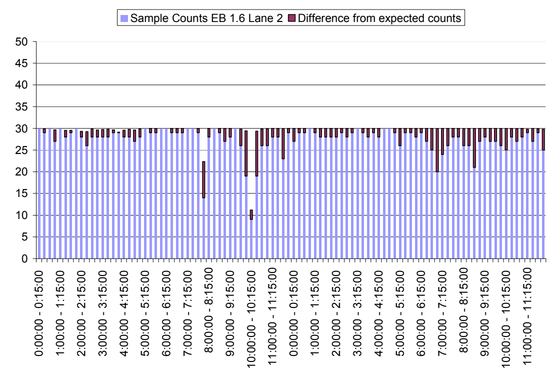

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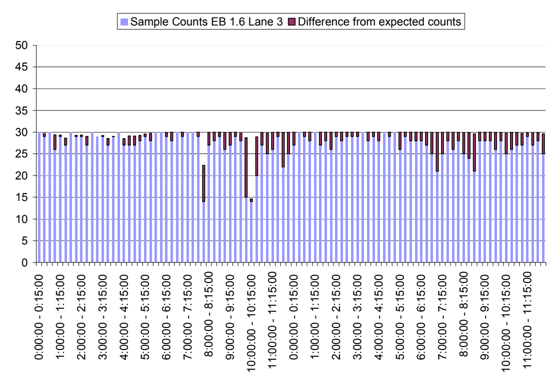

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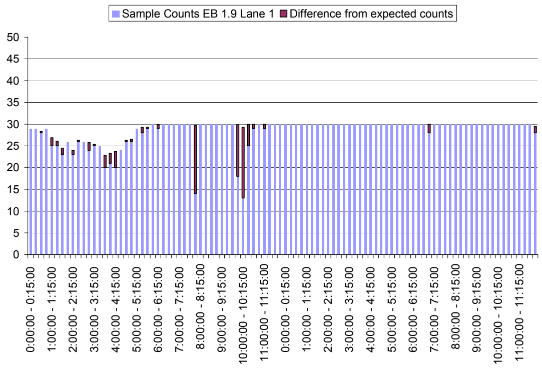

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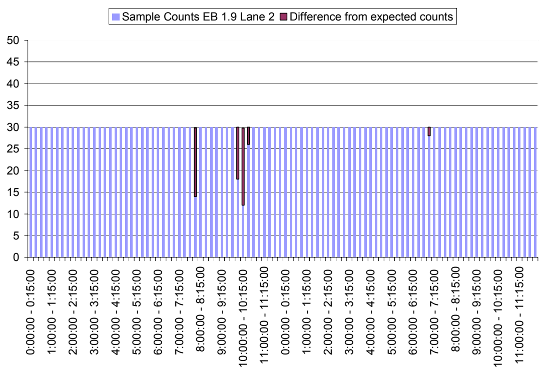

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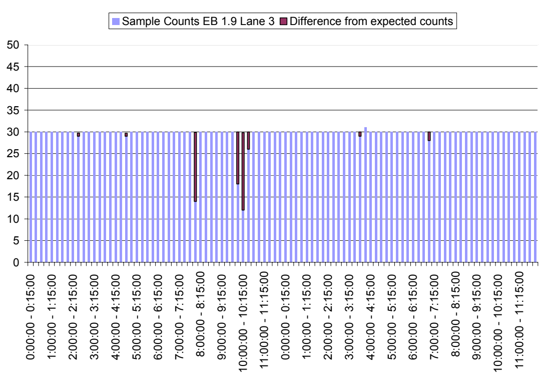
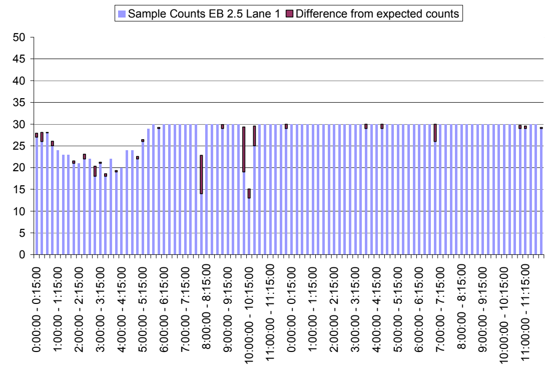


c) Lane 3

Figure B-3: Sample counts and differences from expected counts for RTMS on I-80/94, at EB MP 1.9, on Feb. 25, 2004



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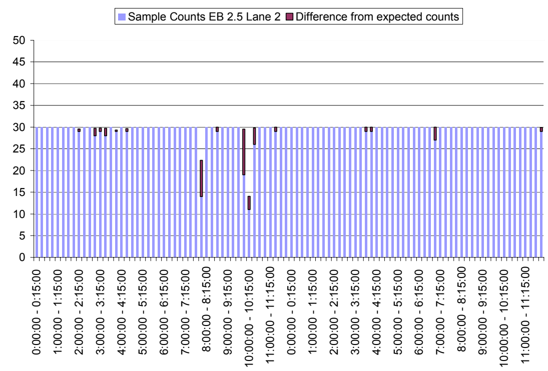

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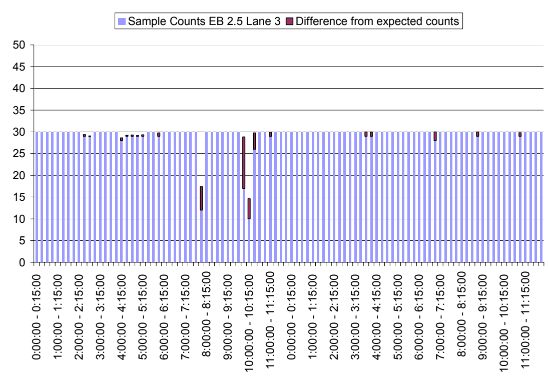

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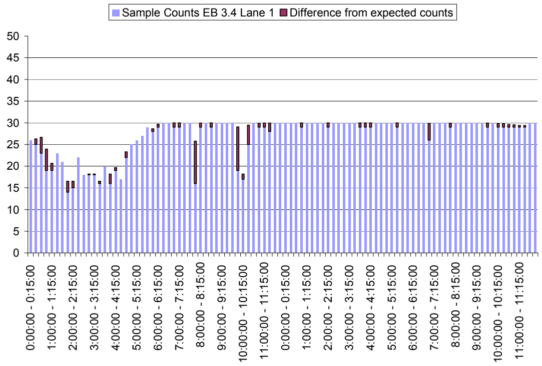
Figure B-4: Sample counts and differences from expected counts for microloop on I-80/94, at EB MP 2.5, on Feb. 25, 2004



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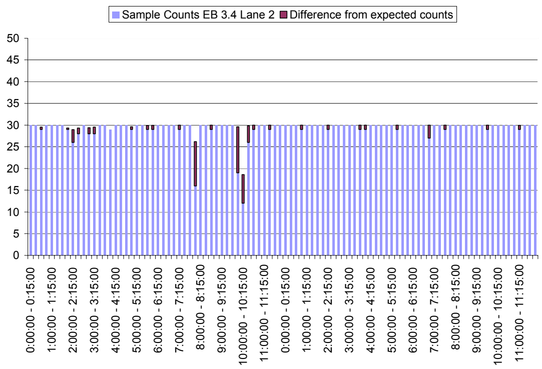

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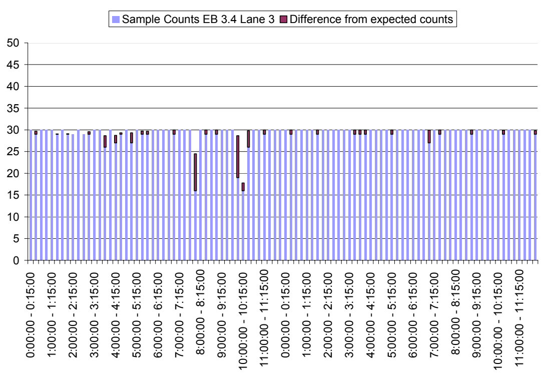
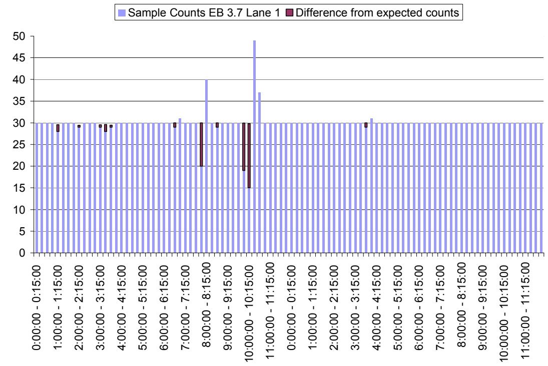


c) Lane 3

Figure B-5: Sample counts and differences from expected counts for microloop on I-80/94, at EB MP 3.4, on Feb. 25, 2004



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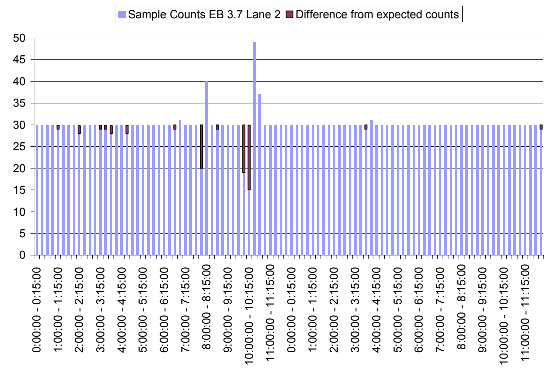

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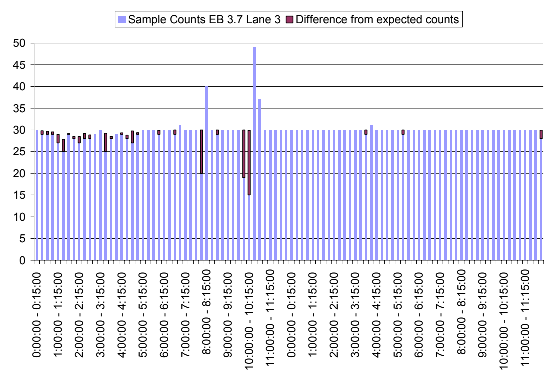

c) Lane 3

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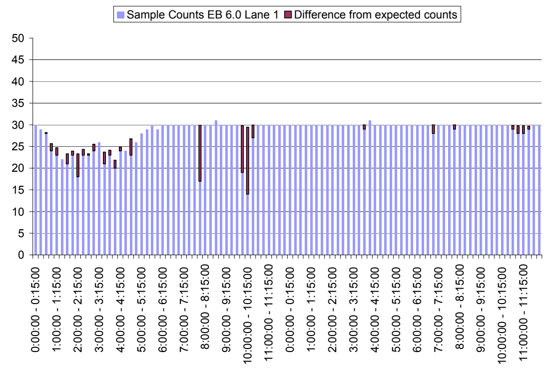

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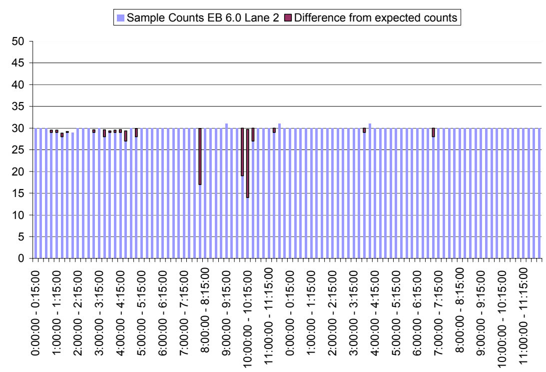
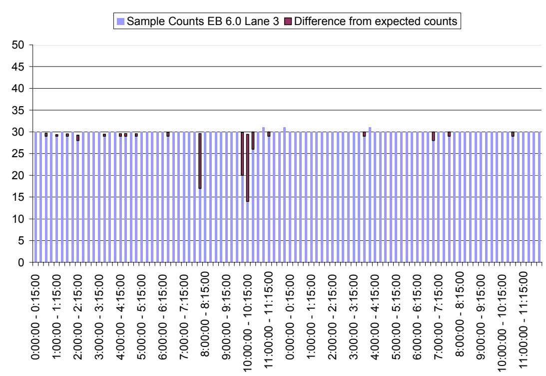
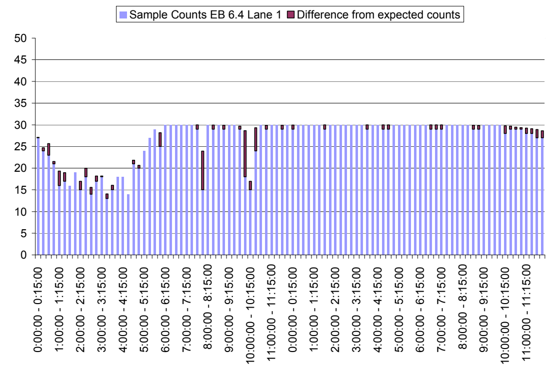


b) Lane 2

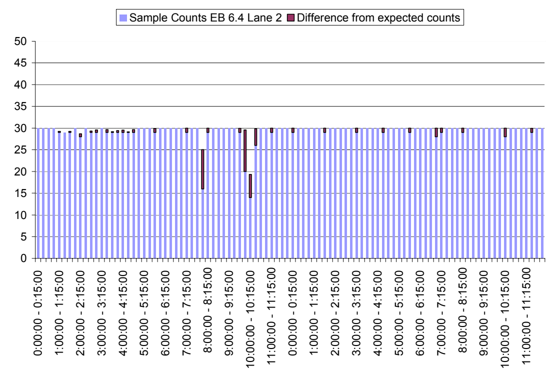


c) Lane 3

Figure B-7: Sample counts and differences from expected counts for RTMS on I-80/94, at EB MP 6.0, on Feb. 25, 2004



a) Lane 1



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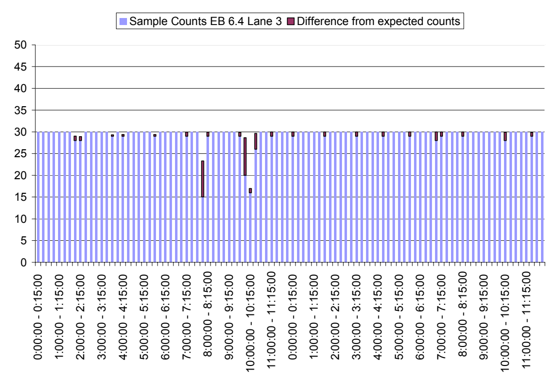
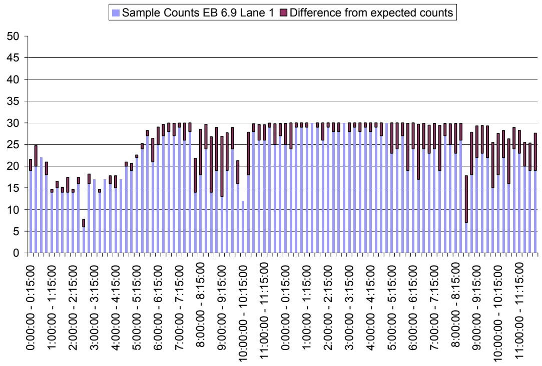
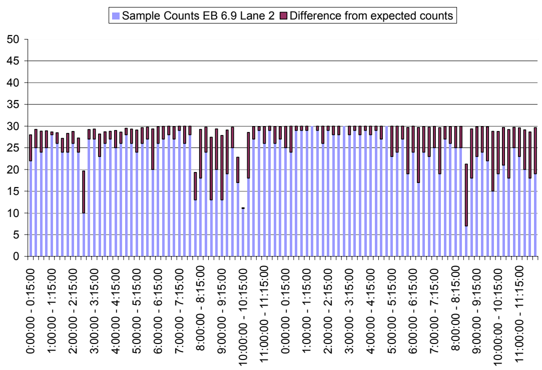


c) Lane 3

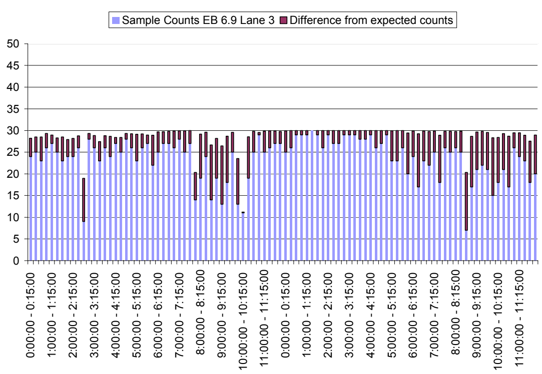
Figure B-8: Sample counts and differences from expected counts for microloop on I-80/94, at EB MP 6.4, on Feb. 25, 2004



a) Lane 1

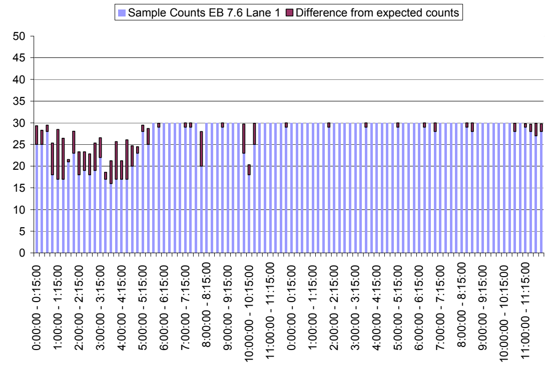


b) Lane 2

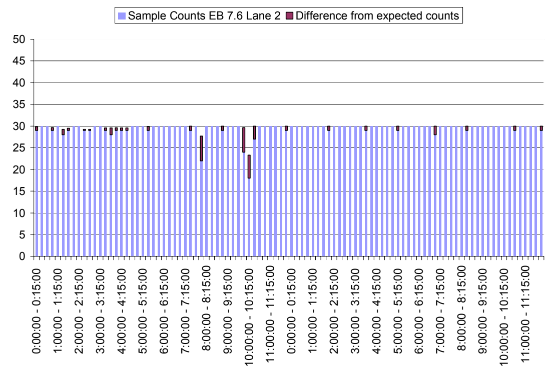


c) Lane 3

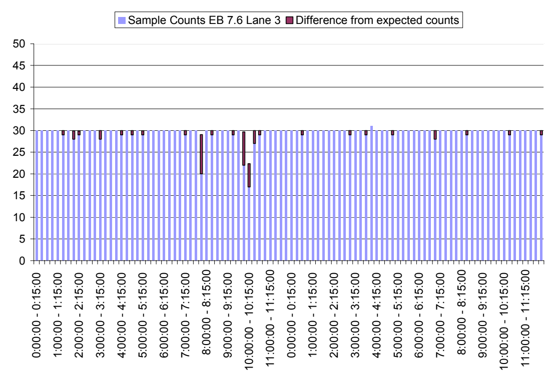
Figure B-9: Sample counts and differences from expected counts for microloop on I-80/94, at EB MP 6.9, on Feb. 25, 2004



a) Lane 1

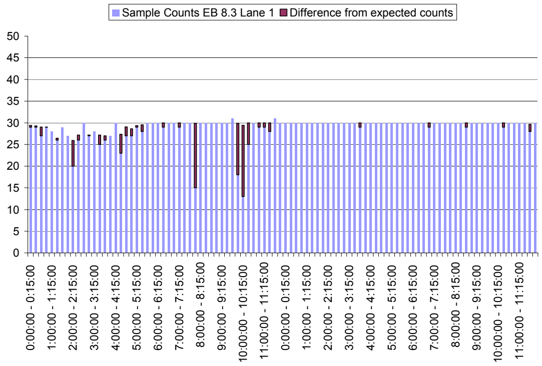


b) Lane 2

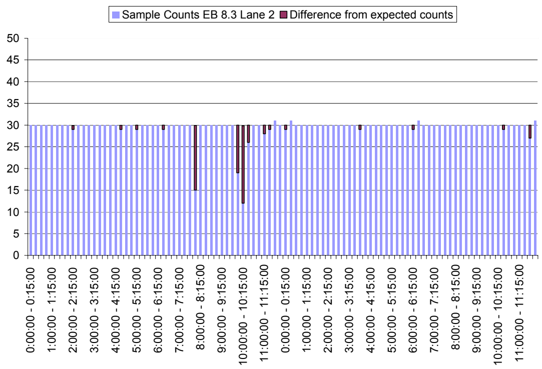


c) Lane 3

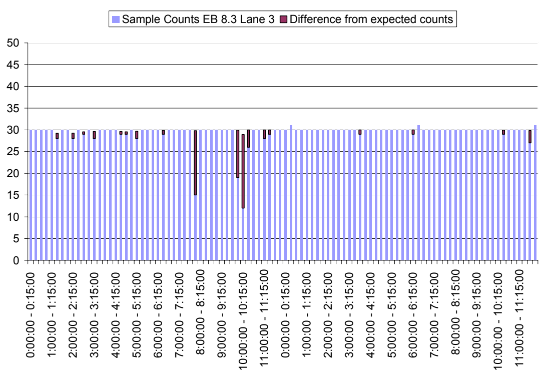
Figure B-10: Sample counts and differences from expected counts for microloop on I-80/94, at EB MP 7.6, on Feb. 25, 2004



a) Lane 1

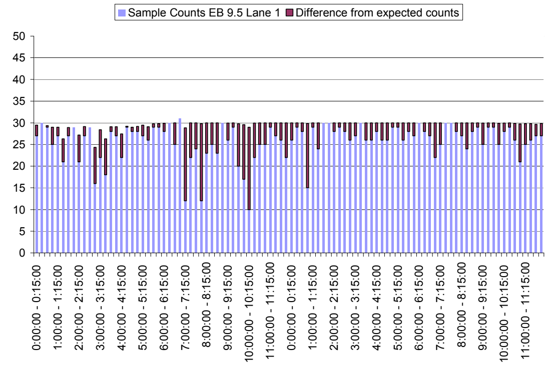


b) Lane 2

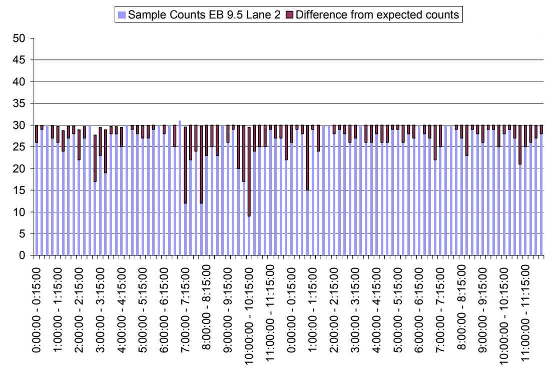


c) Lane 3

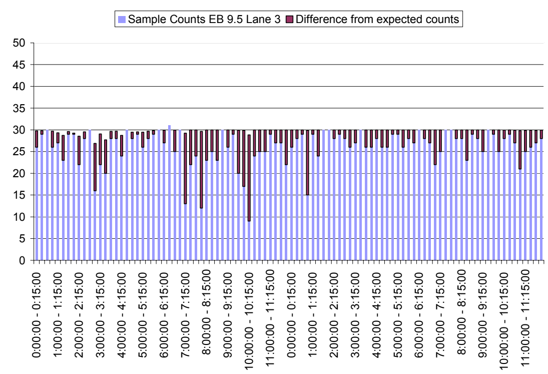
Figure B-11: Sample counts and differences from expected counts for RTMS on I-80/94, at EB MP 8.3, on Feb. 25, 2004



a) Lane 1

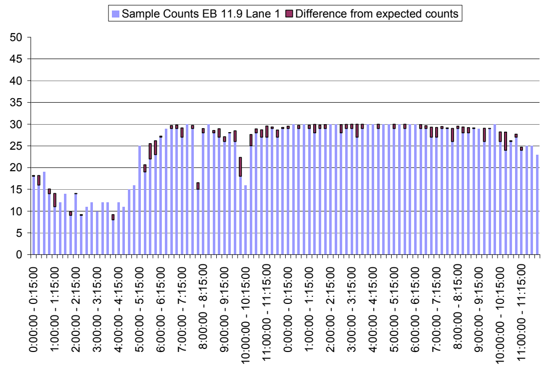


b) Lane 2

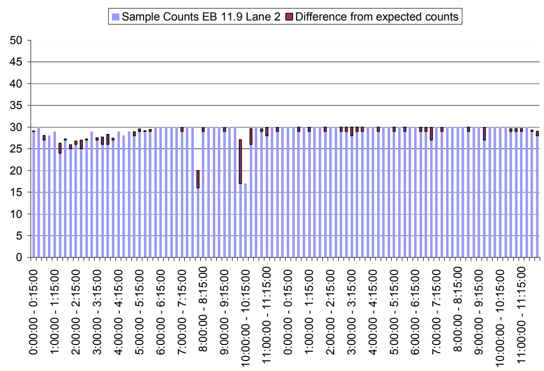


c) Lane 3

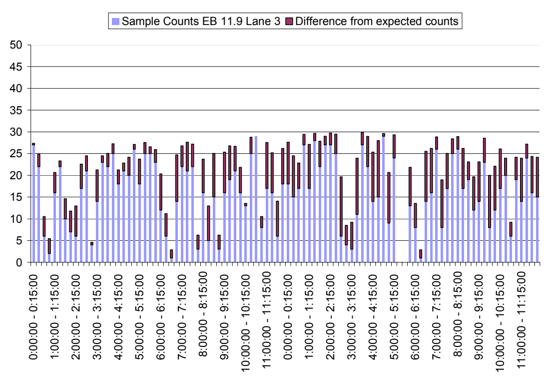
Figure B-12: Sample counts and differences from expected counts for RTMS on I-80/94, at EB MP 9.5, on Feb. 25, 2004



a) Lane 1

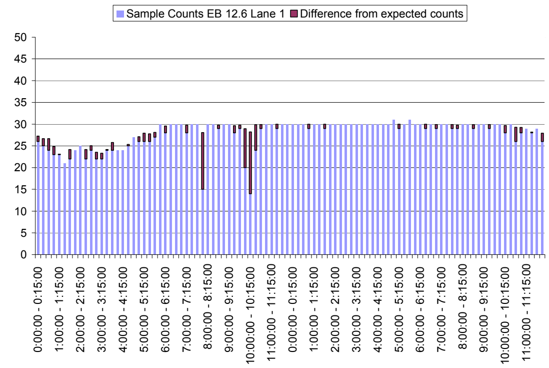


b) Lane 2

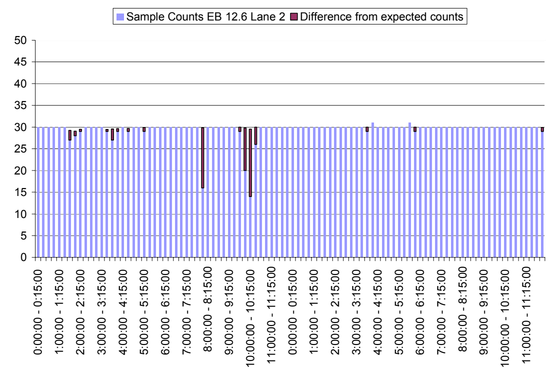


c) Lane 3

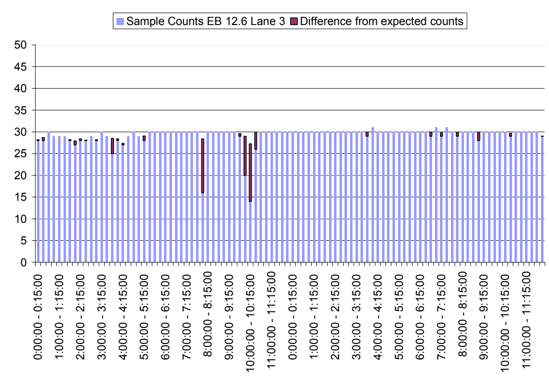
Figure B-13: Sample counts and differences from expected counts for microloop on I-80/94, at EB MP 11.9, on Feb. 25, 2004



a) Lane 1

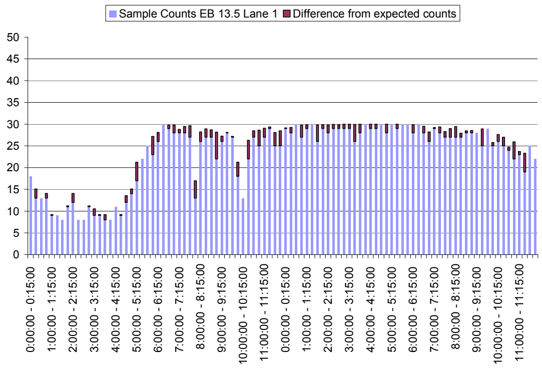


b) Lane 2

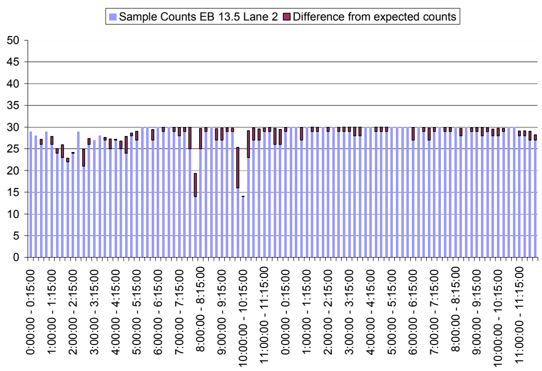


c) Lane 3

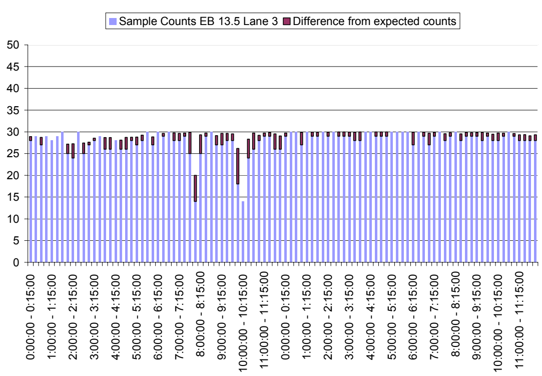
Figure B-14: Sample counts and differences from expected counts for microloop on I-80/94, at EB MP 12.6, on Feb. 25, 2004



a) Lane 1

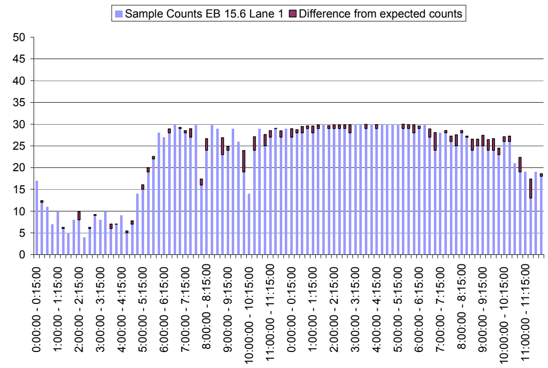


b) Lane 2

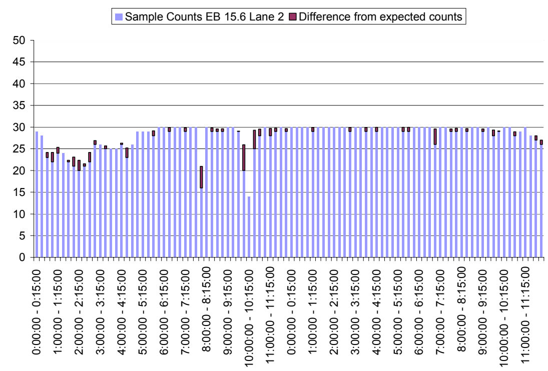


c) Lane 3

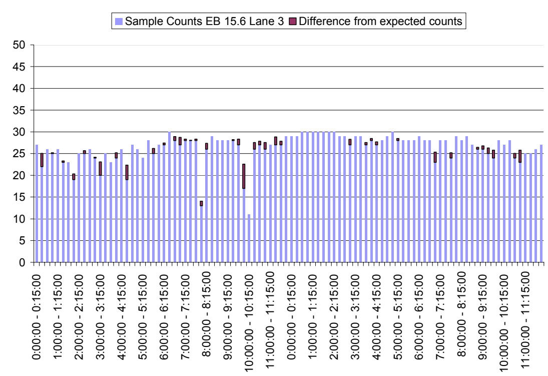
Figure B-15: Sample counts and differences from expected counts for microloop on I-80/94, at EB MP 13.5, on Feb. 25, 2004



a) Lane 1

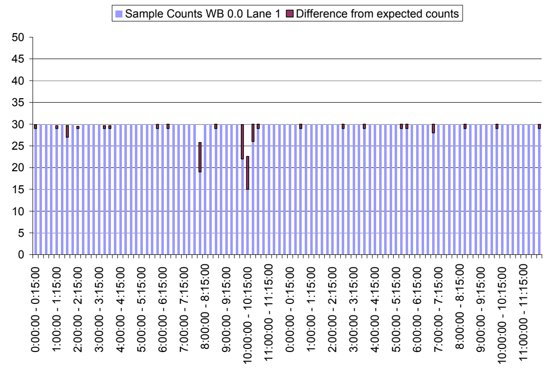


b) Lane 2

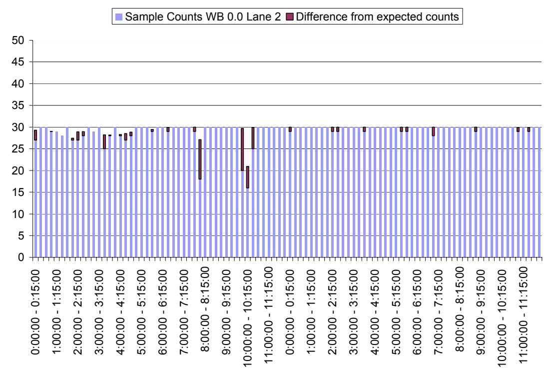


c) Lane 3

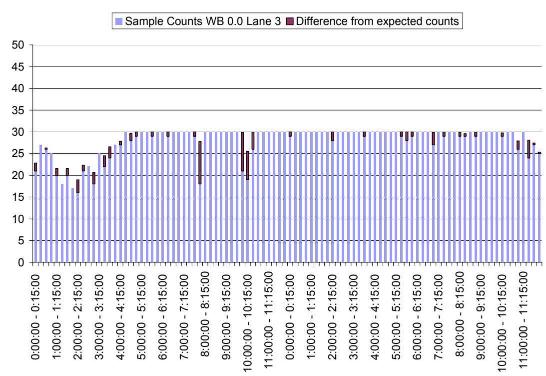
Figure B-16: Sample counts and differences from expected counts for microloop on I-80/94, at EB MP 15.6, on Feb. 25, 2004



a) Lane 1

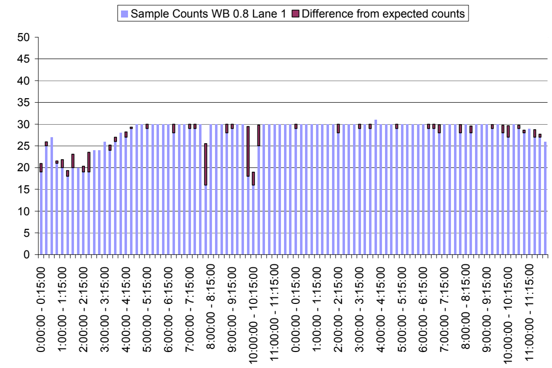


b) Lane 2

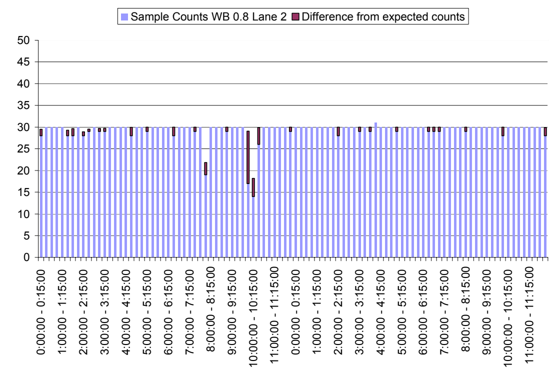


c) Lane 3

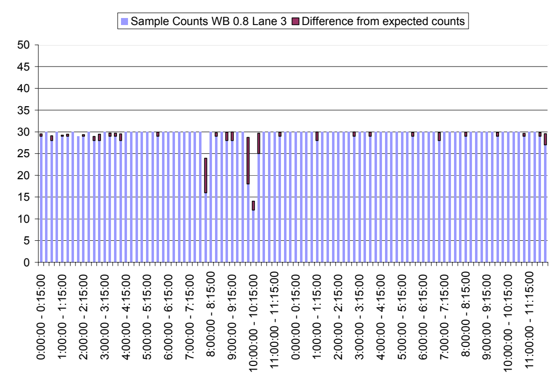
Figure B-17: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 0.0, on Feb. 25, 2004



a) Lane 1

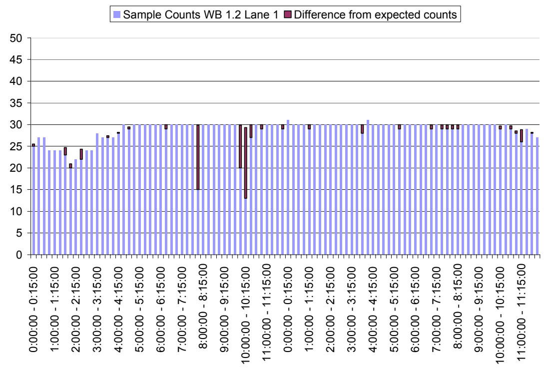


b) Lane 2

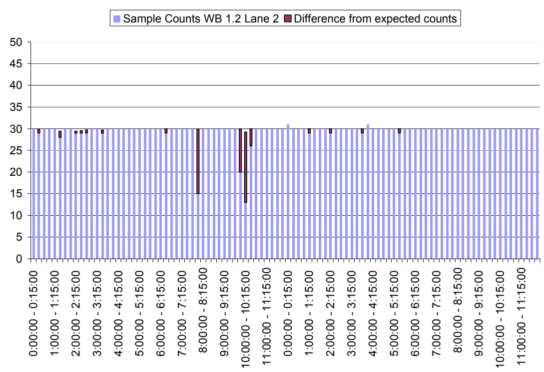


c) Lane 3

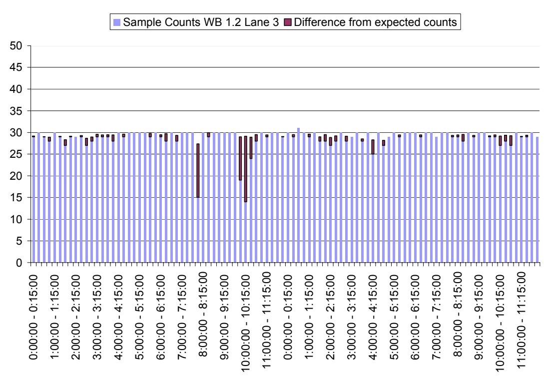
Figure B-18: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 0.8, on Feb. 25, 2004



a) Lane 1

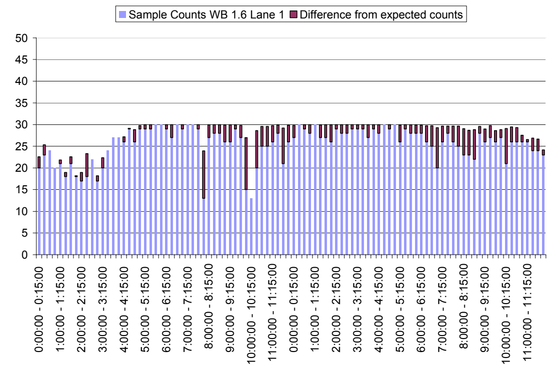


b) Lane 2

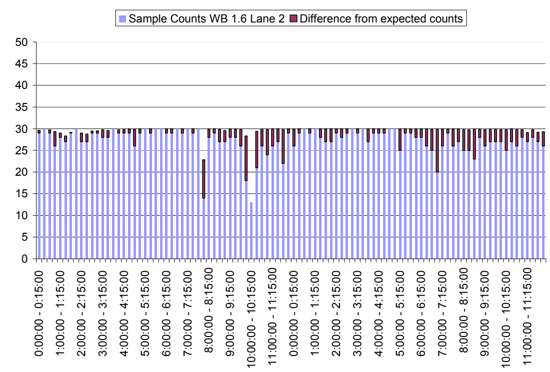


c) Lane 3

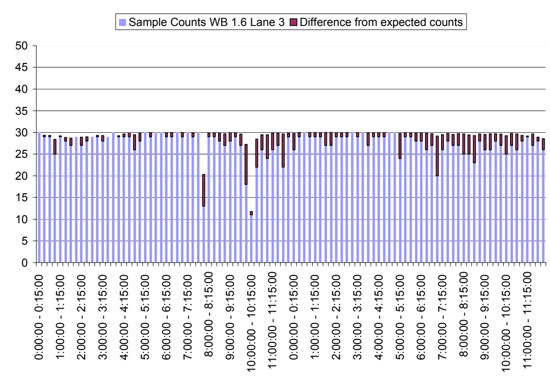
Figure B-19: Sample counts and differences from expected counts for RTMS on I-80/94, at WB MP 1.2, on Feb. 25, 2004



a) Lane 1

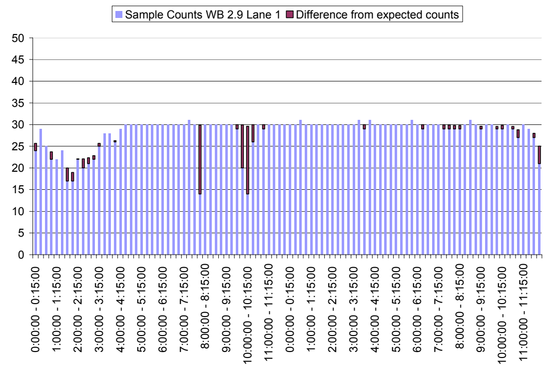


b) Lane 2

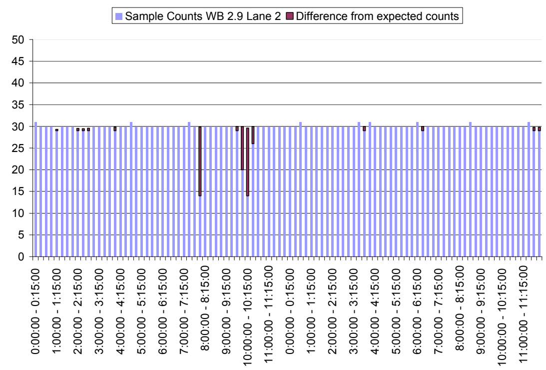


c) Lane 3

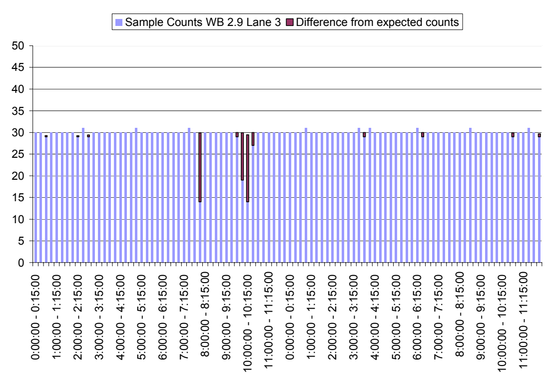
Figure B-20: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 1.6, on Feb. 25, 2004



a) Lane 1

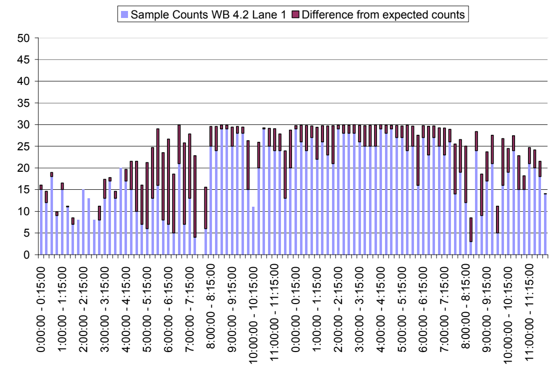


b) Lane 2

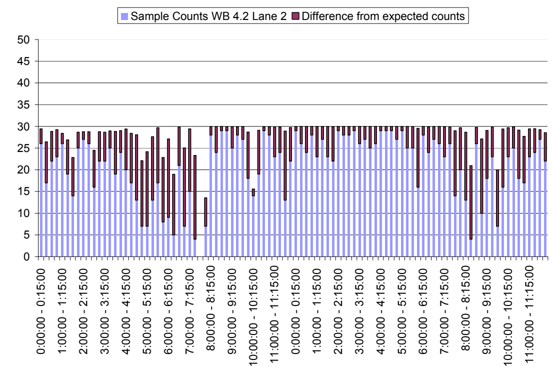


c) Lane 3

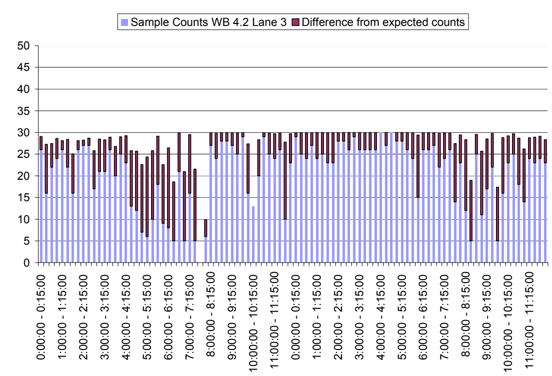
Figure B-21: Sample counts and differences from expected counts for RTMS on I-80/94, at WB MP 2.9, on Feb. 25, 2004



a) Lane 1

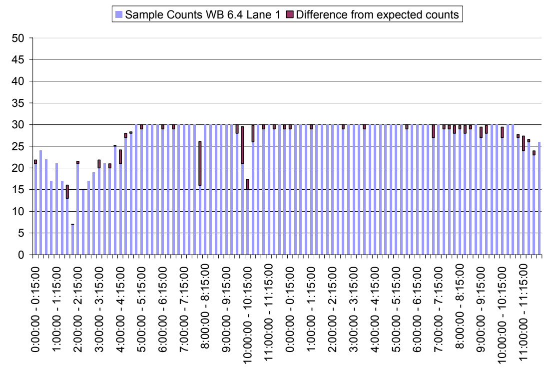


b) Lane 2

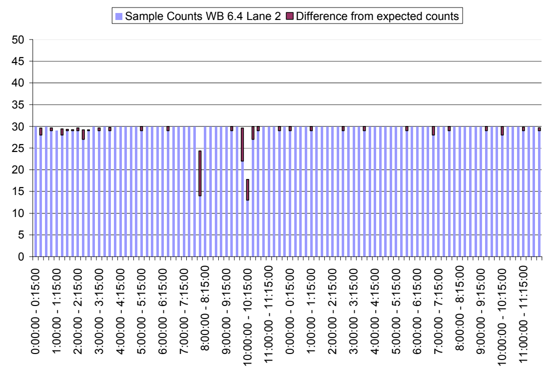


c) Lane 3

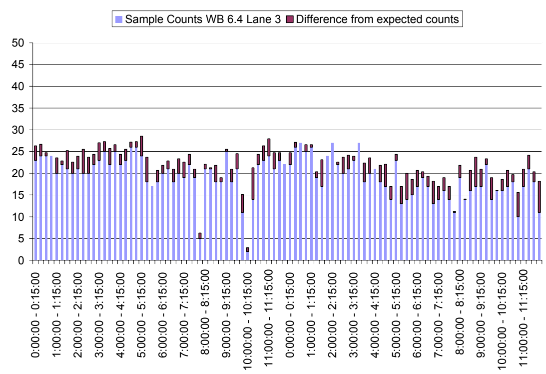
Figure B-22: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 4.2, on Feb. 25, 2004



a) Lane 1

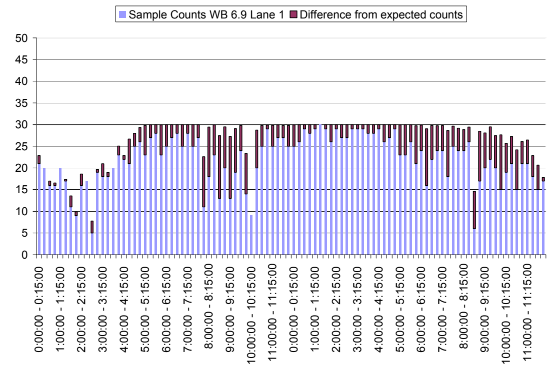


b) Lane 2

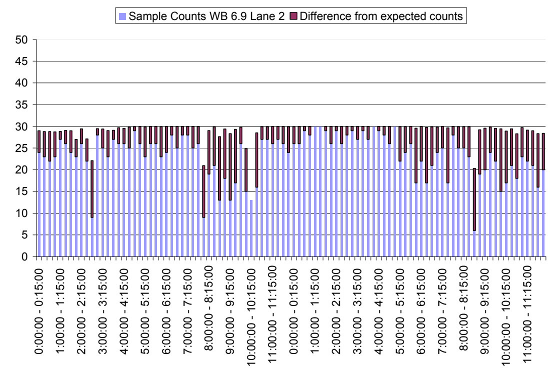


c) Lane 3

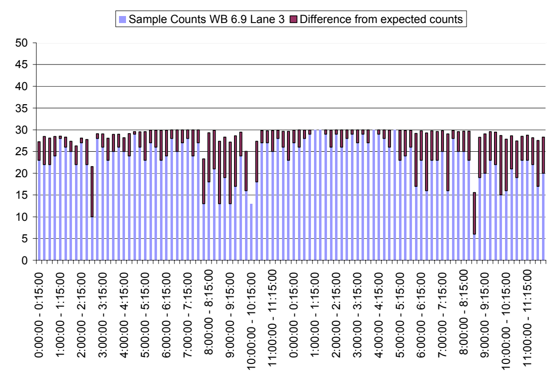
Figure B-23: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 6.4, on Feb. 25, 2004



a) Lane 1

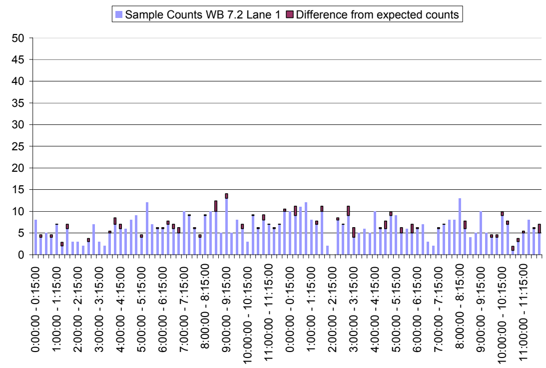


b) Lane 2

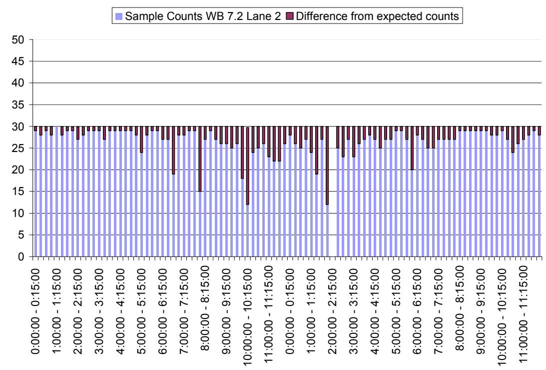


c) Lane 3

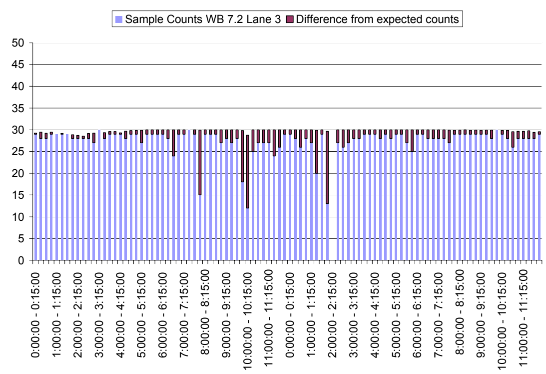
Figure B-24: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 6.9, on Feb. 25, 2004



a) Lane 1

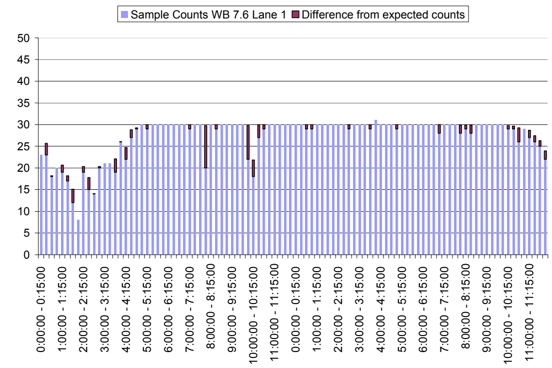


b) Lane 2

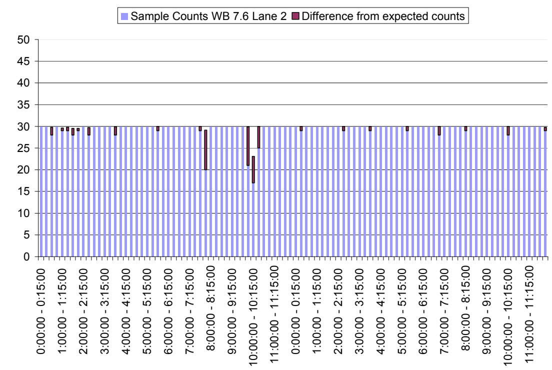


c) Lane 3

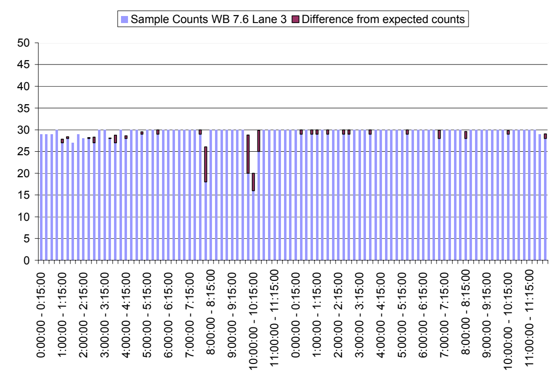
Figure B-25: Sample counts and differences from expected counts for RTMS on I-80/94, at WB MP 7.2, on Feb. 25, 2004



a) Lane 1

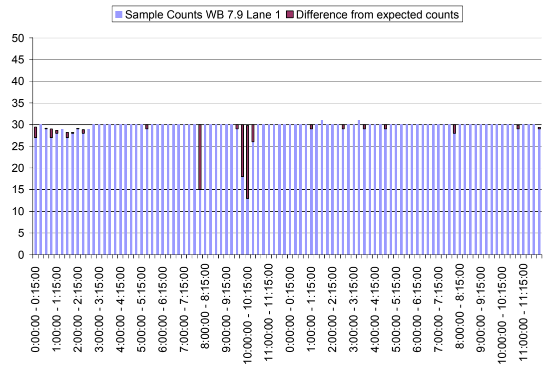


b) Lane 2

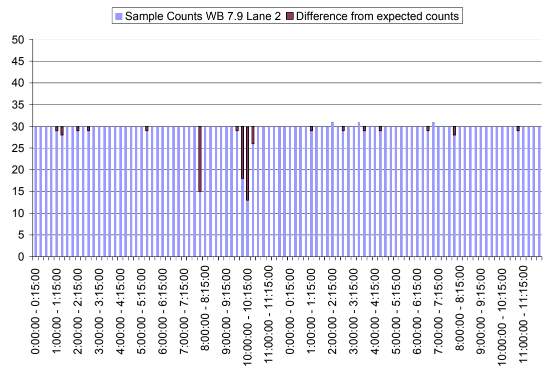


c) Lane 3

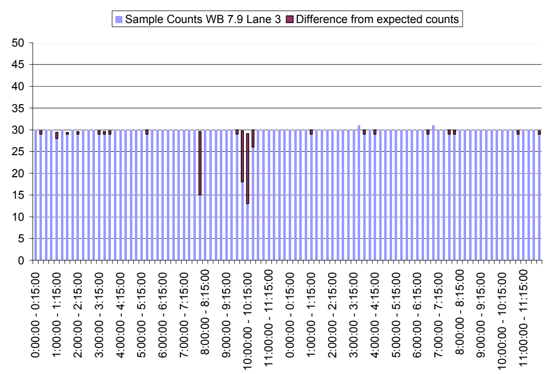
Figure B-26: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 7.6, on Feb. 25, 2004



a) Lane 1

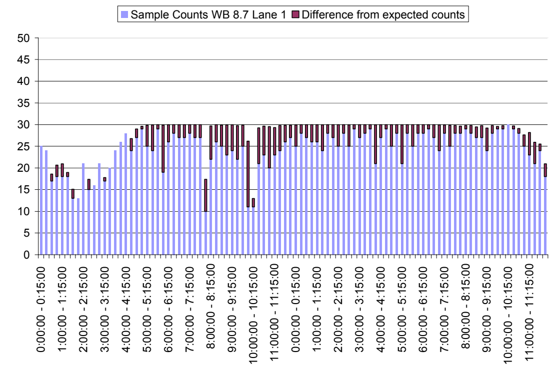


b) Lane 2

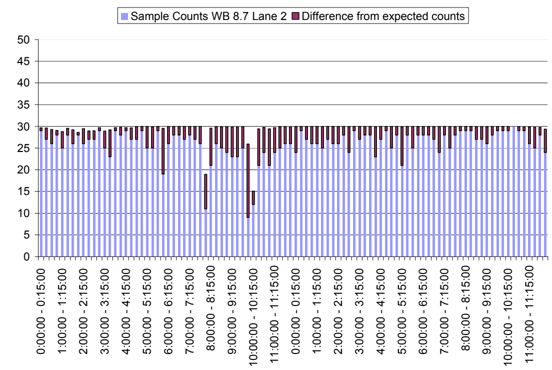


c) Lane 3

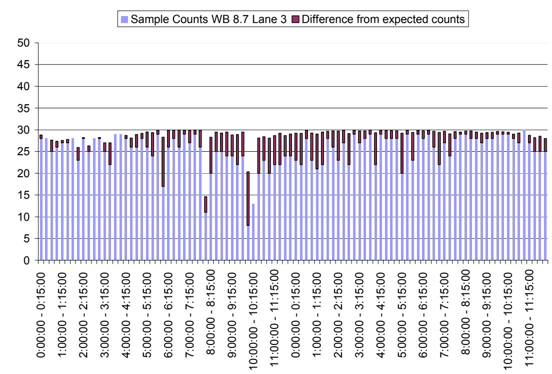
Figure B-27: Sample counts and differences from expected counts for RTMS on I-80/94, at WB MP 7.9, on Feb. 25, 2004



a) Lane 1

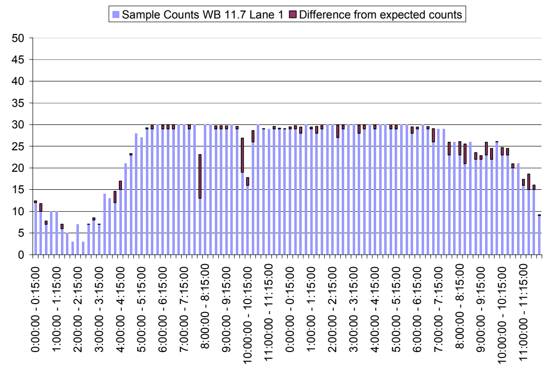


b) Lane 2

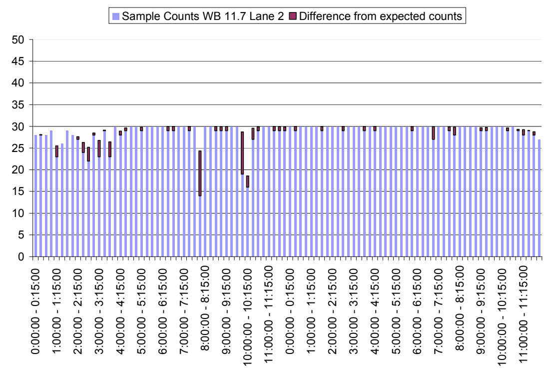


c) Lane 3

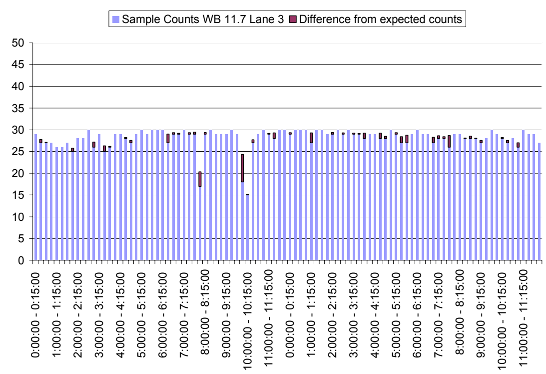
Figure B-28: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 8.7, on Feb. 25, 2004



a) Lane 1

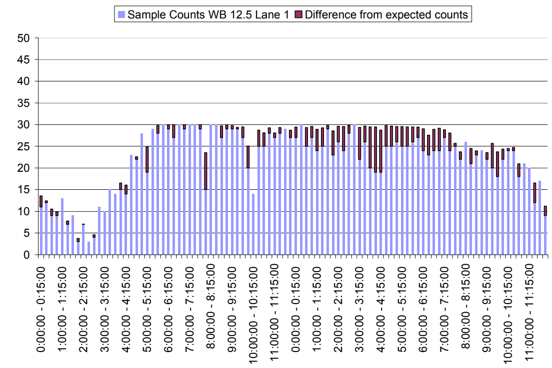


b) Lane 2

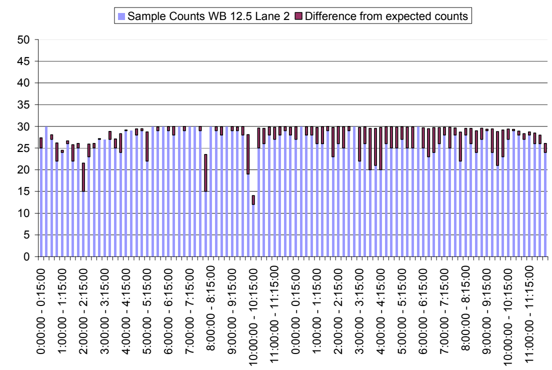


c) Lane 3

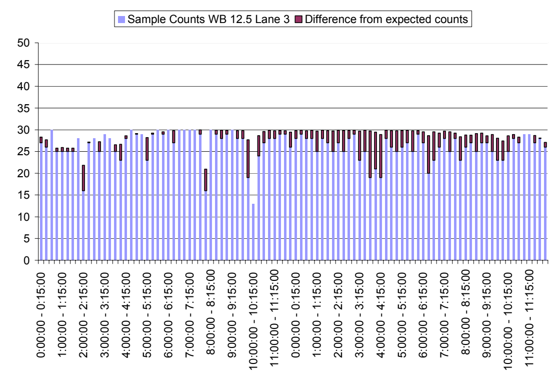
Figure B-29: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 11.7, on Feb. 25, 2004



a) Lane 1

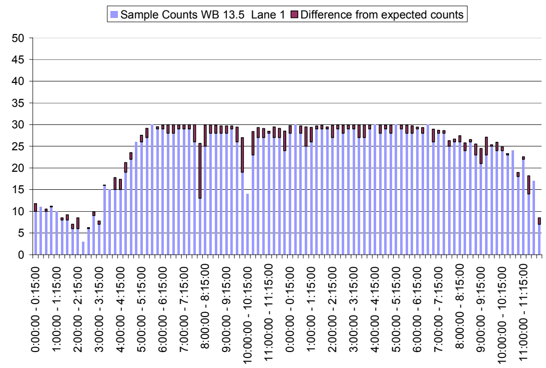


b) Lane 2

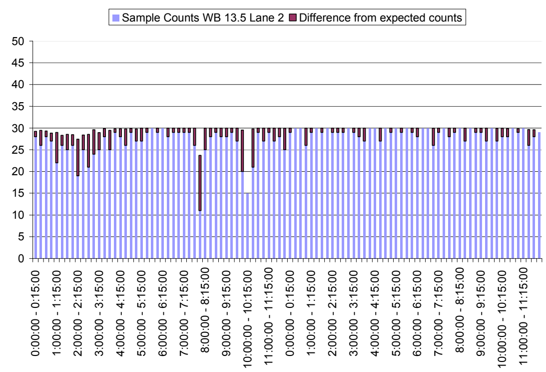


c) Lane 3

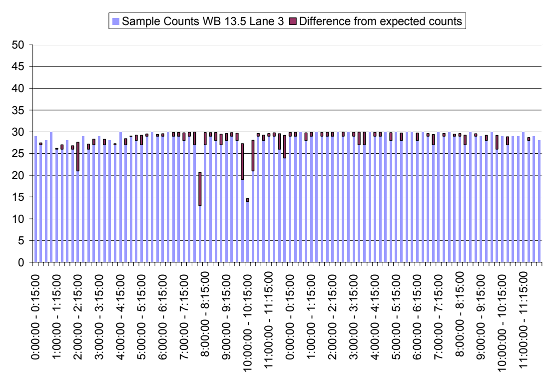
Figure B-30: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 12.5, on Feb. 25, 2004



a) Lane 1

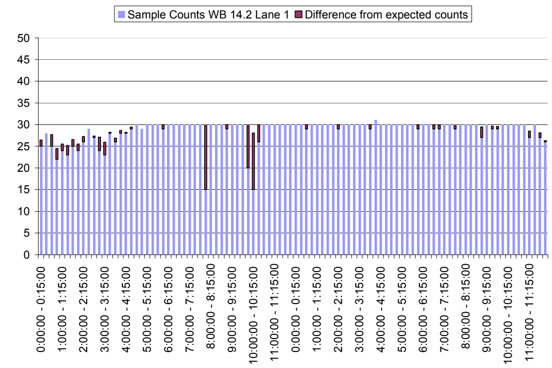


b) Lane 2

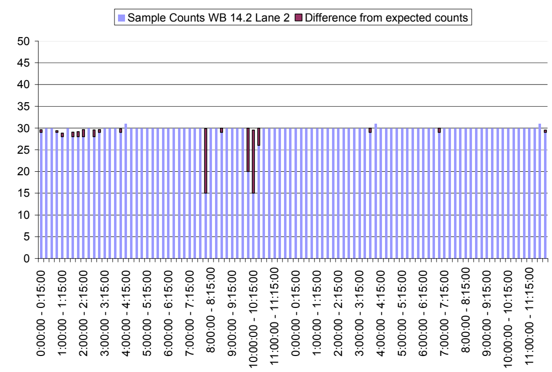


c) Lane 3

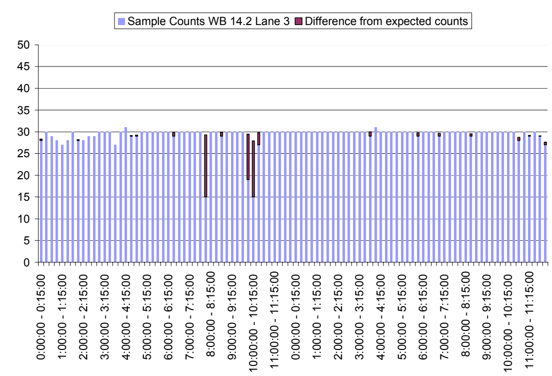
Figure B-31: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 13.5, on Feb. 25, 2004



a) Lane 1

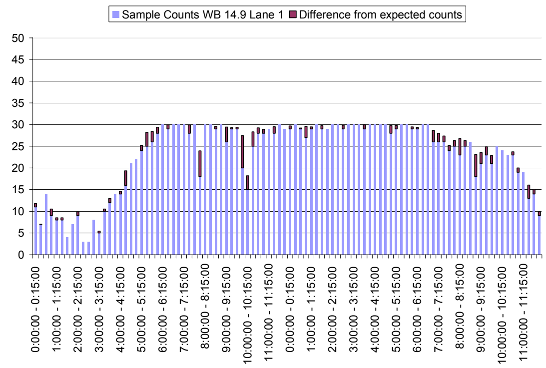


b) Lane 2

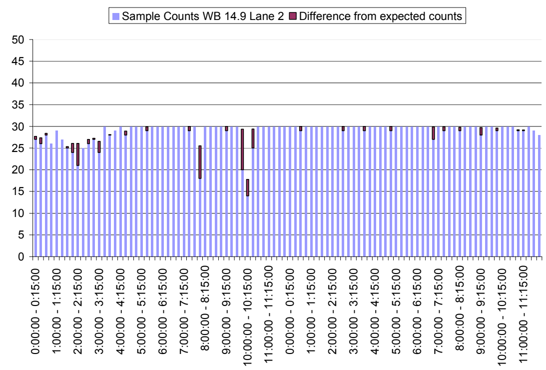


c) Lane 3

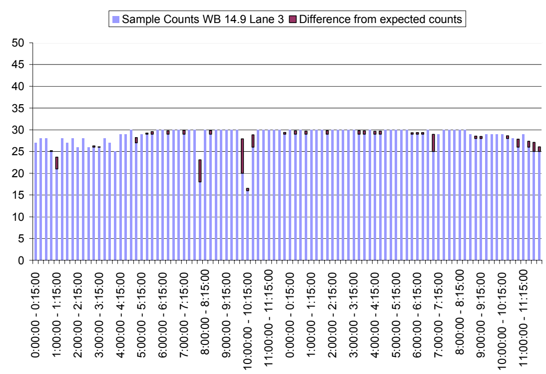
Figure B-32: Sample counts and differences from expected counts for RTMS on I-80/94, at WB MP 14.2, on Feb. 25, 2004



a) Lane 1



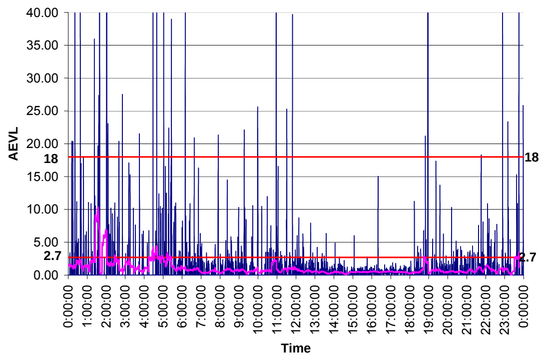
b) Lane 2



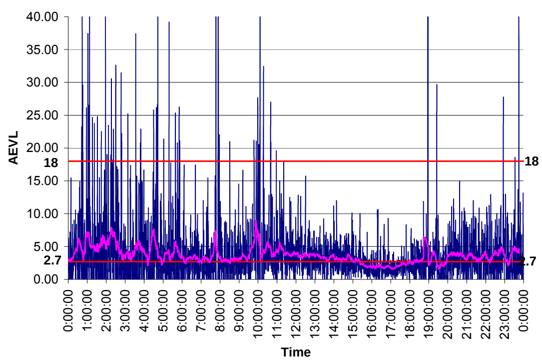
c) Lane 3

Figure B-33: Sample counts and differences from expected counts for microloop on I-80/94, at WB MP 14.9, on Feb. 25, 2004

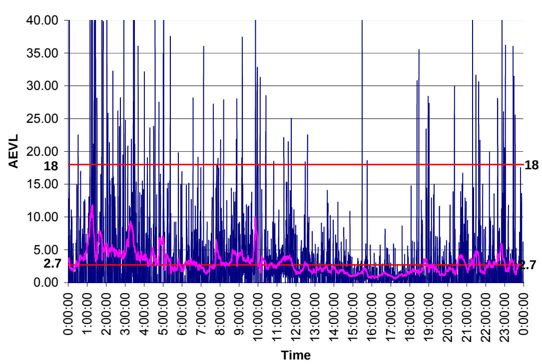
Appendix C. AEVL Test



a) Lane 1

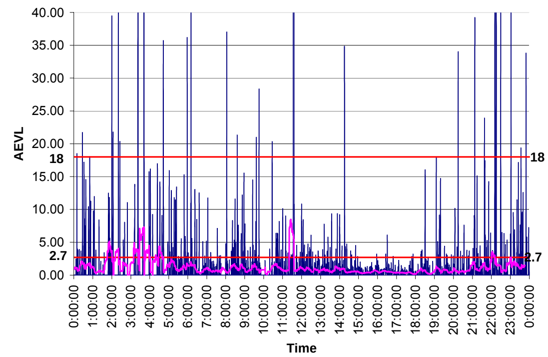


b) Lane 2

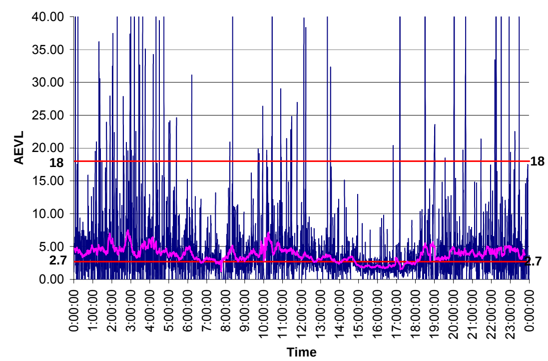


c) Lane 3

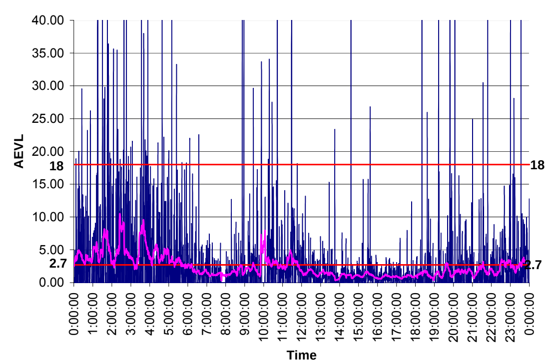
Figure C-1: Average Vehicle Length (m) for microloop on I-80/94, at EB MP 1.0, on Feb 25, 2004



a) Lane 1

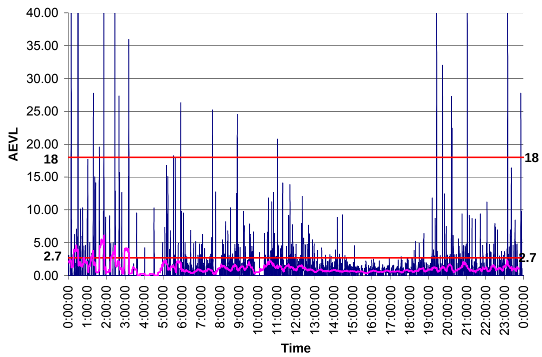


b) Lane 2

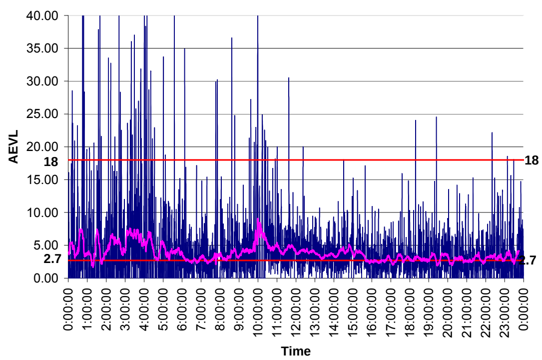


c) Lane 3

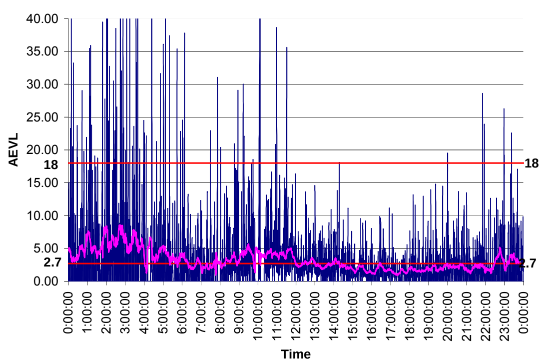
Figure C-2: Average Vehicle Length (m) for microloop on I-80/94, at EB MP 1.6, on Feb 25, 2004



a) Lane 1

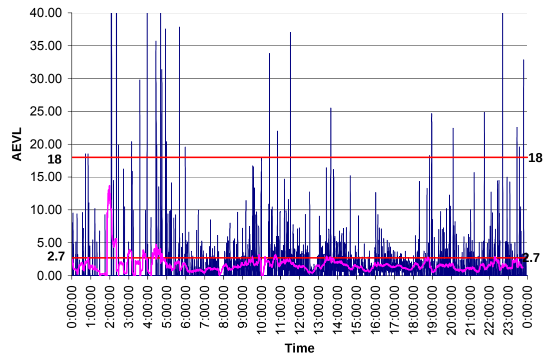


b) Lane 2

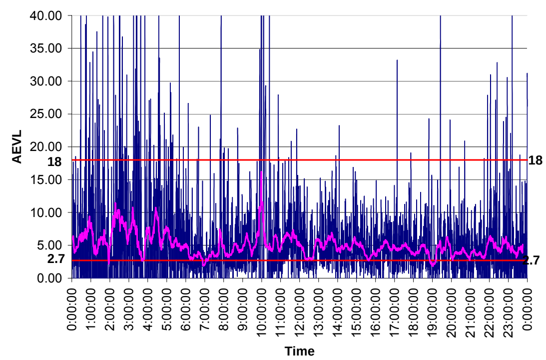


c) Lane 3

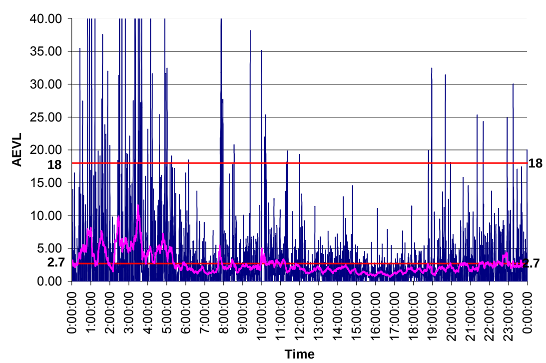
Figure C-3: Average Vehicle Length (m) for microloop on I-80/94, at EB MP 2.5, on Feb 25, 2004



a) Lane 1

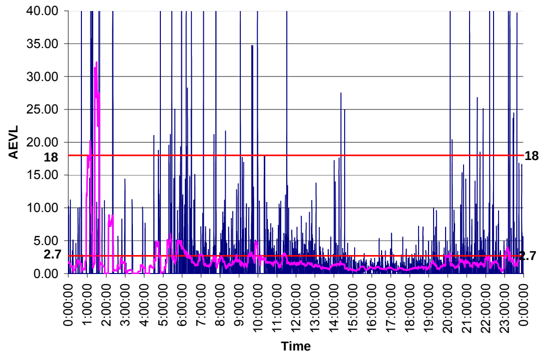


b) Lane 2

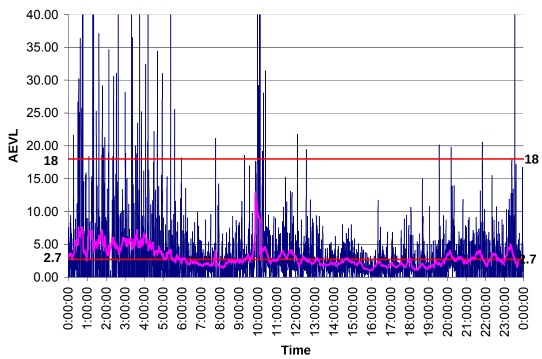


c) Lane 3

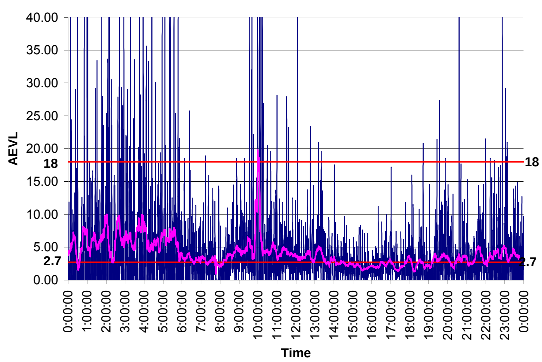
Figure C-4: Average Vehicle Length (m) for microloop on I-80/94, at EB MP 3.4, on Feb 25, 2004



a) Lane 1

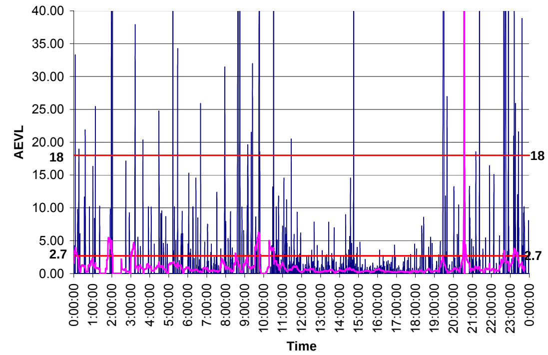


b) Lane 2

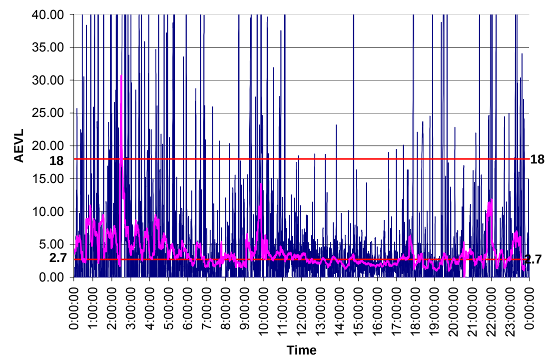


c) Lane 3

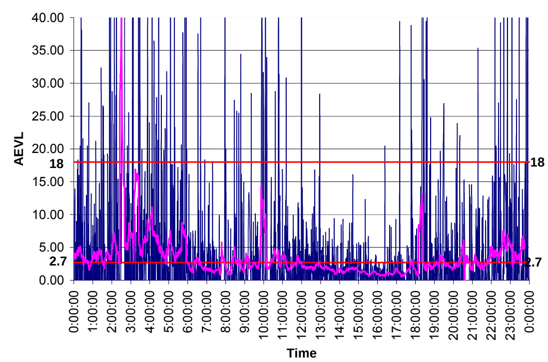
Figure C-5: Average Vehicle Length (m) for microloop on I-80/94, at EB MP 6.4, on Feb 25, 2004



a) Lane 1

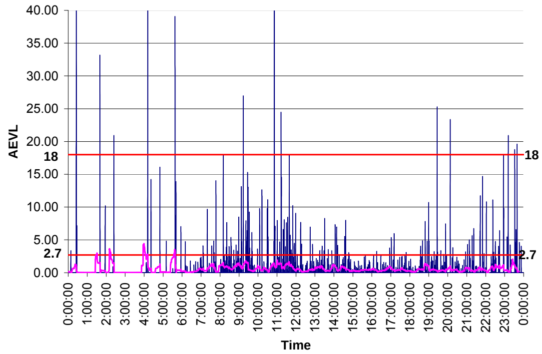


b) Lane 2

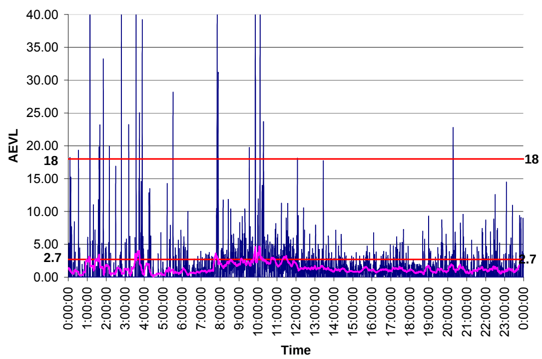


c) Lane 3

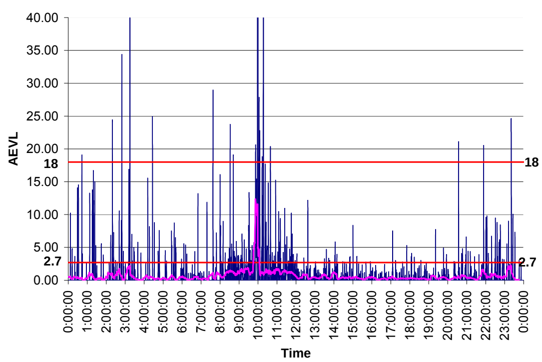
Figure C-6: Average Vehicle Length (m) for microloop on I-80/94, at EB MP 6.9, on Feb 25, 2004



a) Lane 1

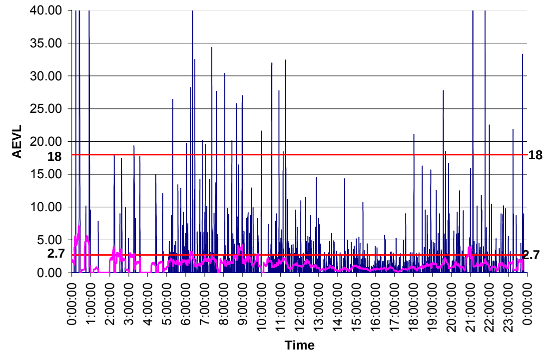


b) Lane 2

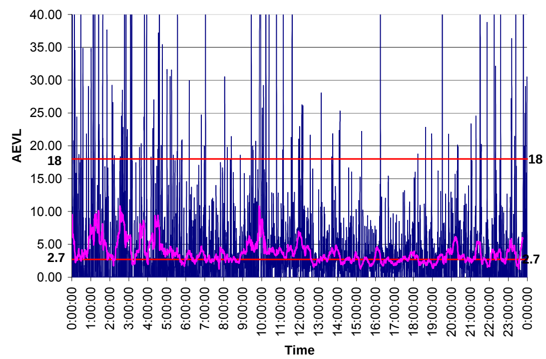


c) Lane 3

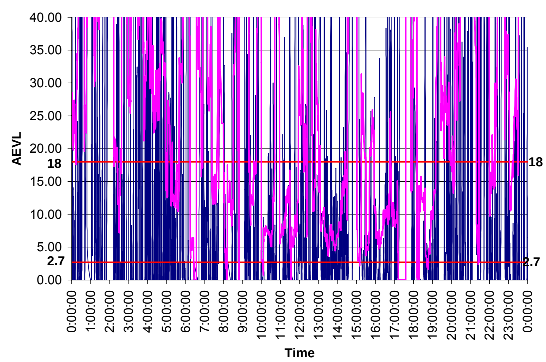
Figure C-7: Average Vehicle Length (m) for microloop on I-80/94, at EB MP 7.6, on Feb 25, 2004



a) Lane 1

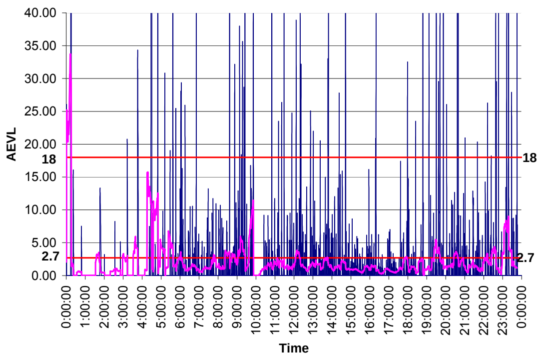


b) Lane 2

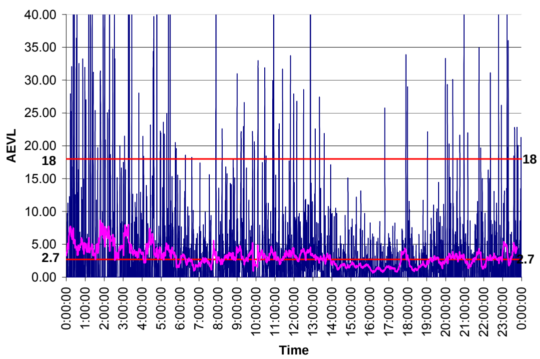


c) Lane 3

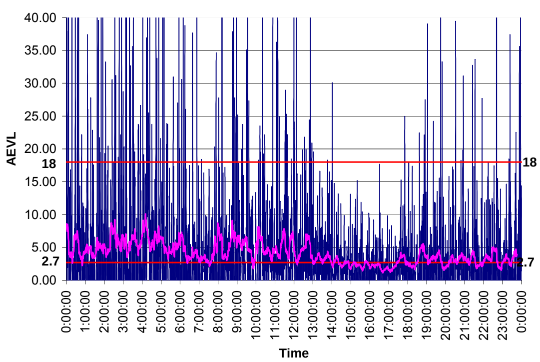
Figure C-8: Average Vehicle Length (m) for microloop on I-80/94, at EB MP 11.9, on Feb 25, 2004



a) Lane 1

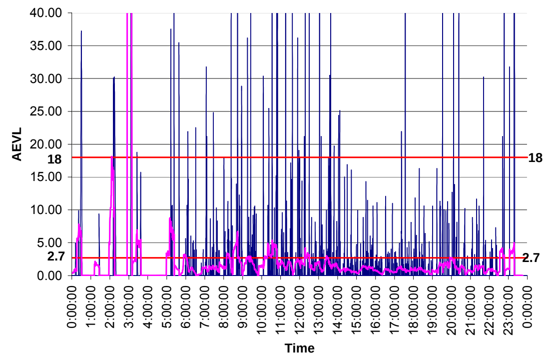


b) Lane 2

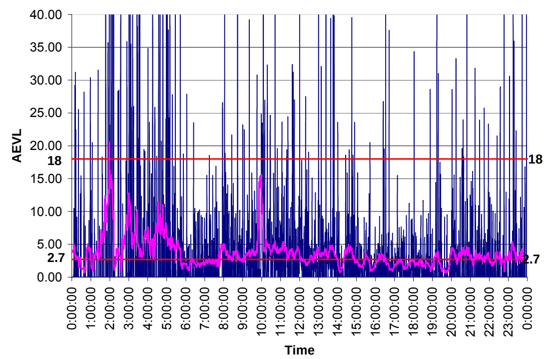


c) Lane 3

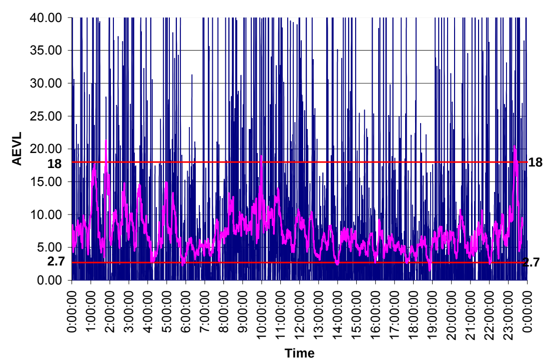
Figure C-9: Average Vehicle Length (m) for microloop on I-80/94, at EB MP 13.5, on Feb 25, 2004



a) Lane 1

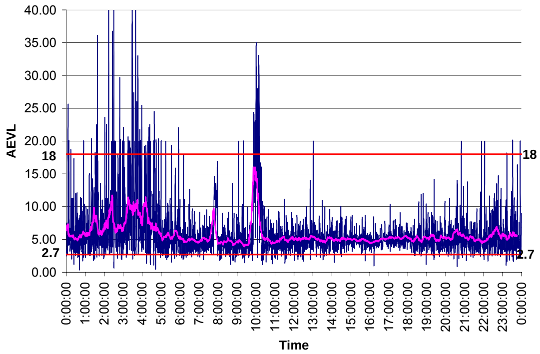


b) Lane 2

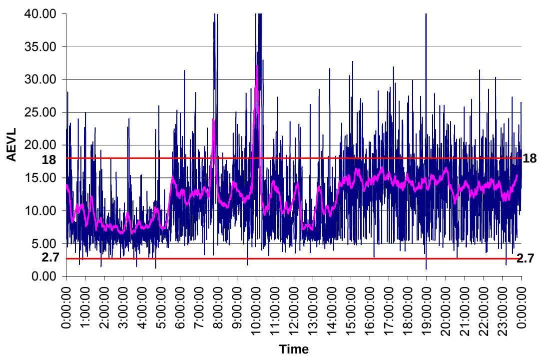


c) Lane 3

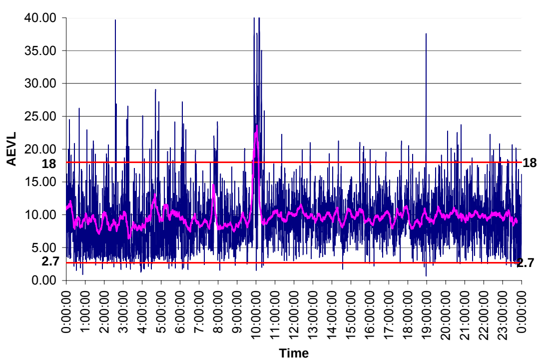
Figure C-10: Average Vehicle Length (m) for microloop on I-80/94, at EB MP 15.6, on Feb 25, 2004



a) Lane 1

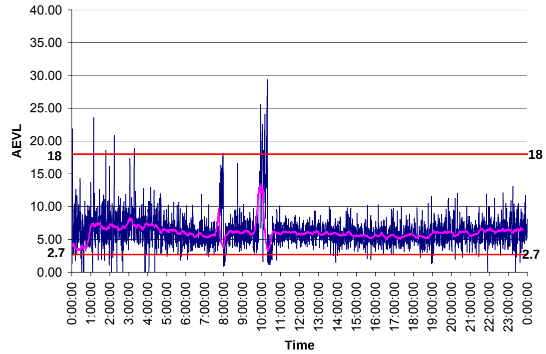


b) Lane 2

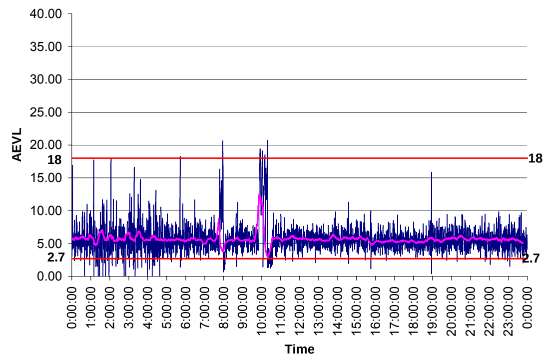


c) Lane 3

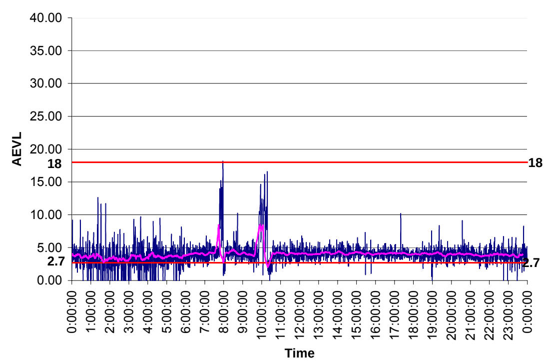
Figure C-11: Average Vehicle Length (m) for RTMS on I-80/94, at EB MP 1.9, on Feb 25, 2004



a) Lane 1

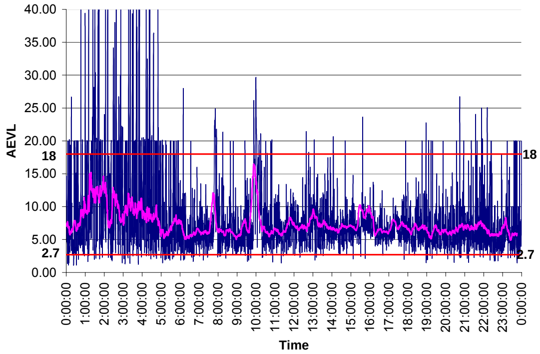


b) Lane 2

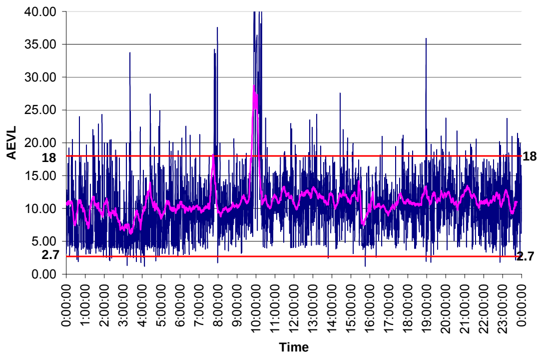


c) Lane 3

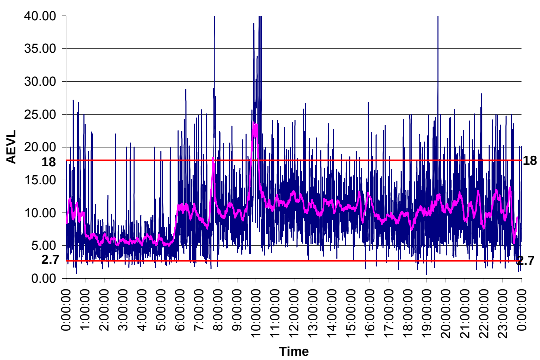
Figure C-12: Average Vehicle Length (m) for wavetronic sensor on I-80/94, at EB MP 3.7, on Feb 25, 2004



a) Lane 1

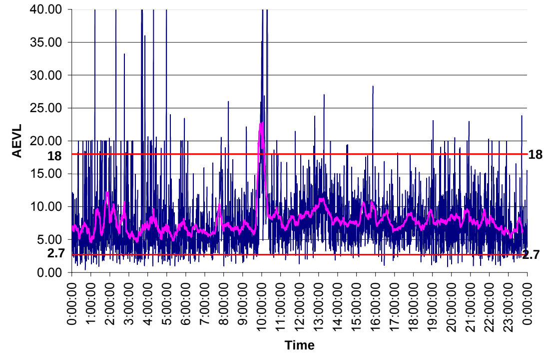


b) Lane 2

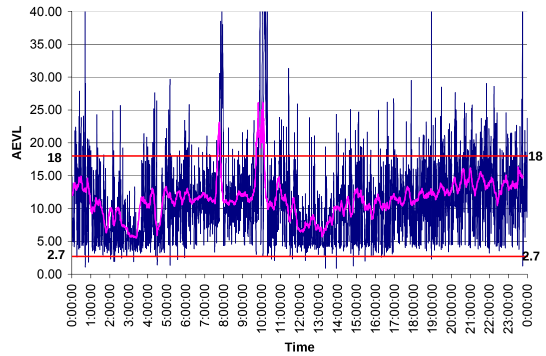


c) Lane 3

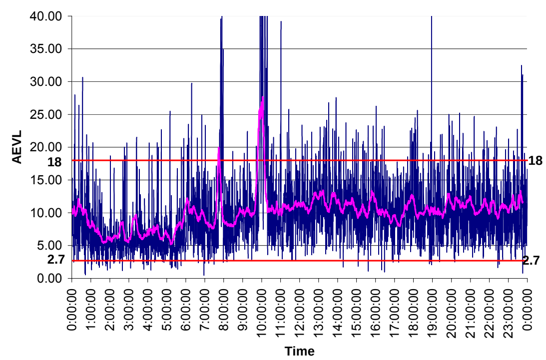
Figure C-13: Average Vehicle Length (m) for RTMS on I-80/94, at EB MP 6.0, on Feb 25, 2004



a) Lane 1

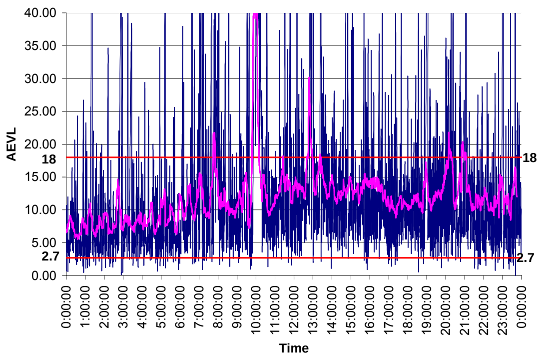


b) Lane 2

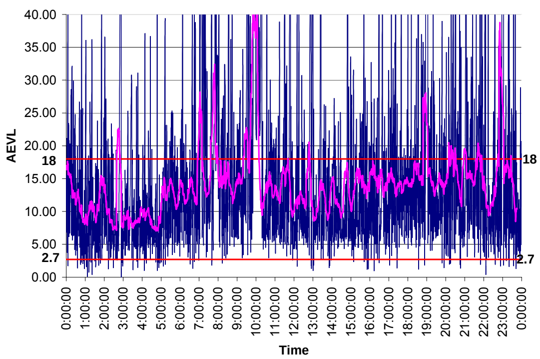


c) Lane 3

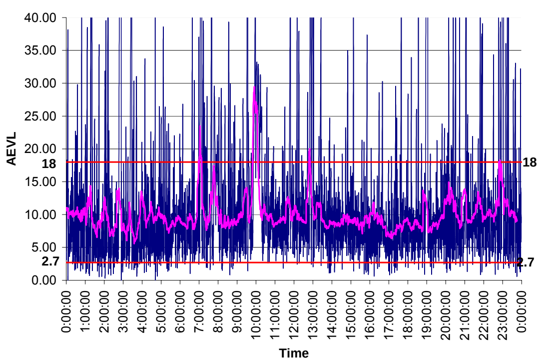
Figure C-14: Average Vehicle Length (m) for RTMS on I-80/94, at EB MP 8.3, on Feb 25, 2004



a) Lane 1

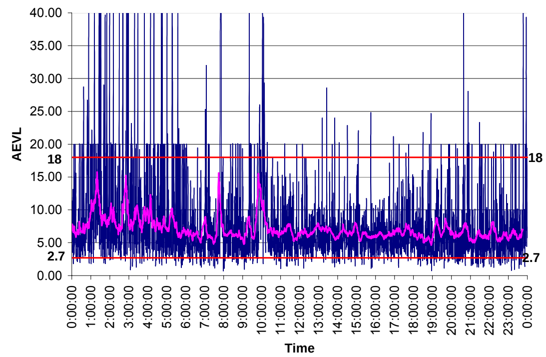


b) Lane 2

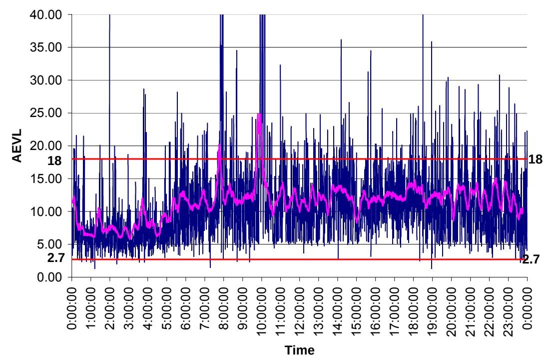


c) Lane 3

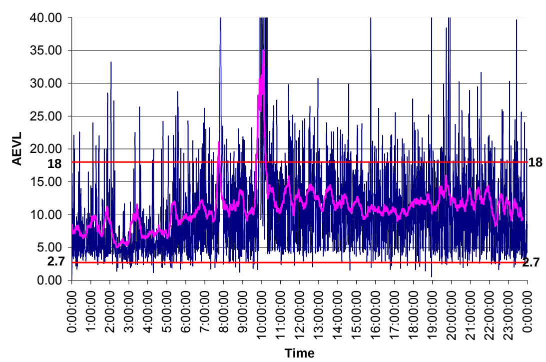
Figure C-15: Average Vehicle Length (m) for RTMS on I-80/94, at EB MP 9.5, on Feb 25, 2004



a) Lane 1

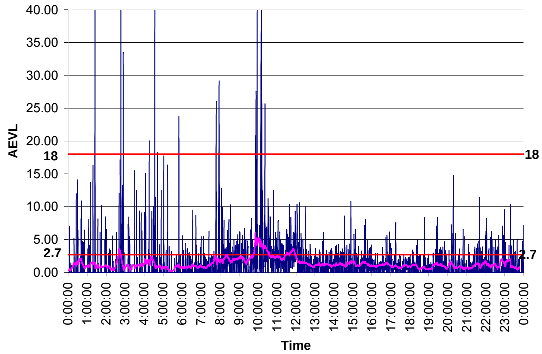


b) Lane 2

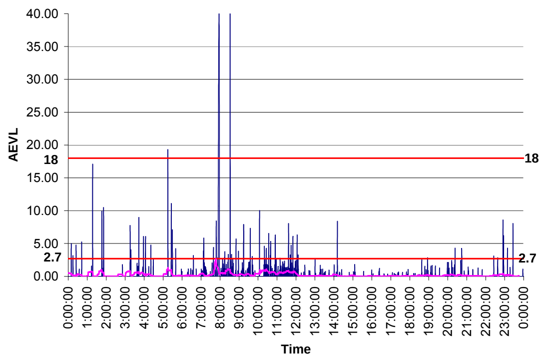


c) Lane 3

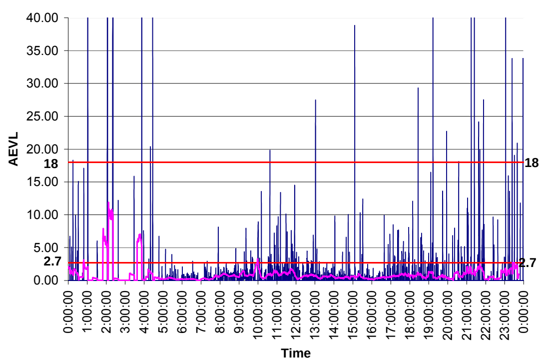
Figure C-16: Average Vehicle Length (m) for RTMS on I-80/94, at EB MP 12.6, on Feb 25, 2004



a) Lane 1

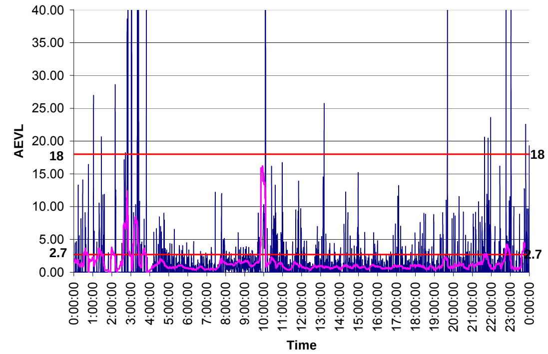


b) Lane 2

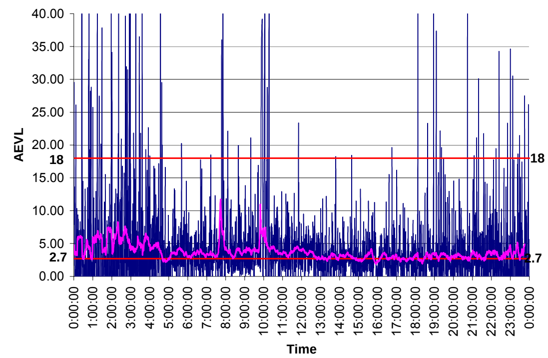


c) Lane 3

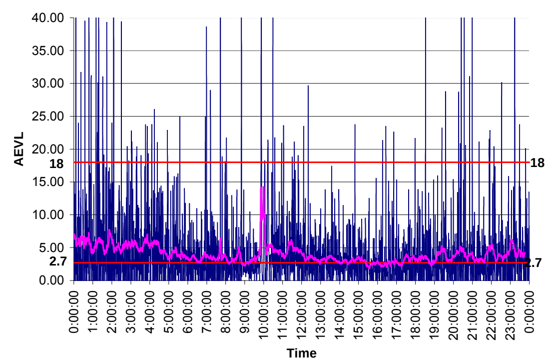
Figure C-17: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 0.0, on Feb 25, 2004



a) Lane 1

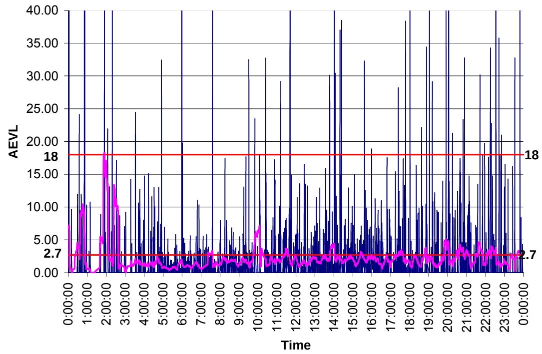


b) Lane 2

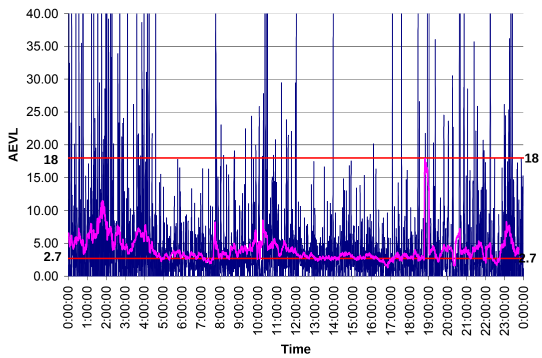


c) Lane 3

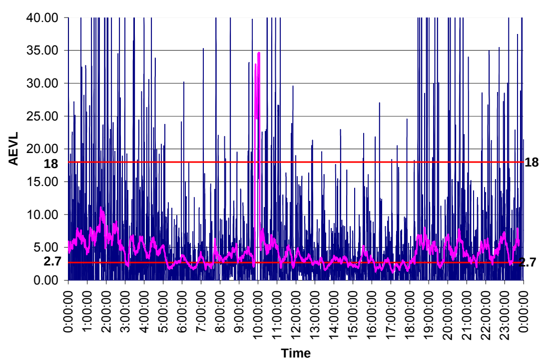
Figure C-18: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 0.8, on Feb 25, 2004



a) Lane 1

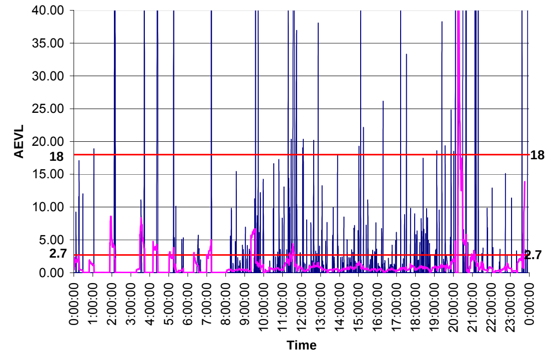


b) Lane 2

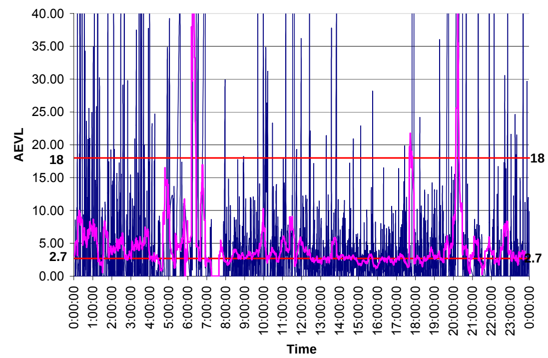


c) Lane 3

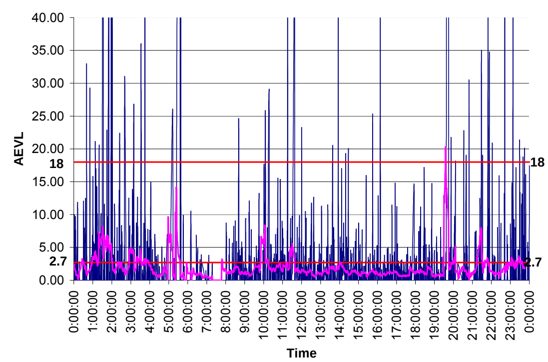
Figure C-19: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 1.6, on Feb 25, 2004



a) Lane 1

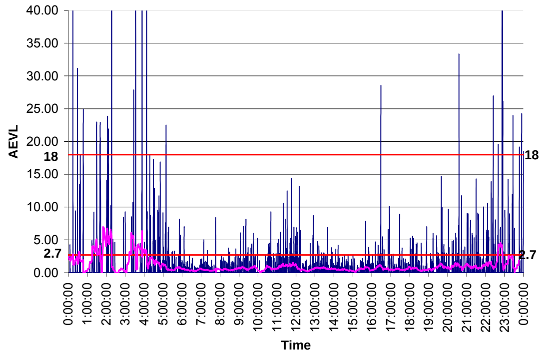


b) Lane 2

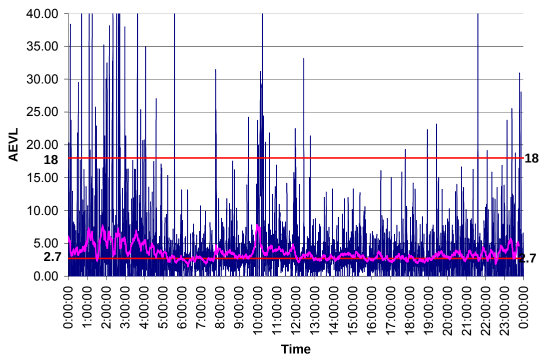


c) Lane 3

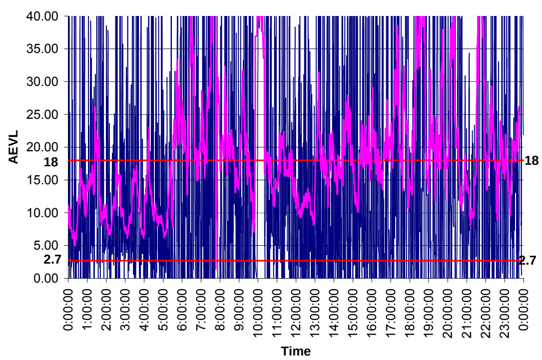
Figure C-20: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 4.2, on Feb 25, 2004



a) Lane 1

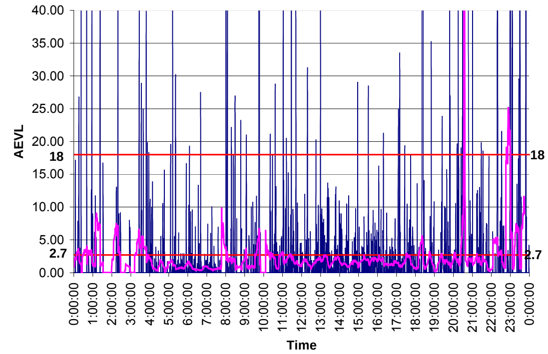


b) Lane 2

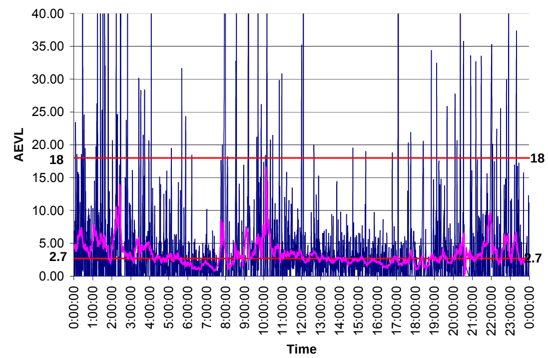


c) Lane 3

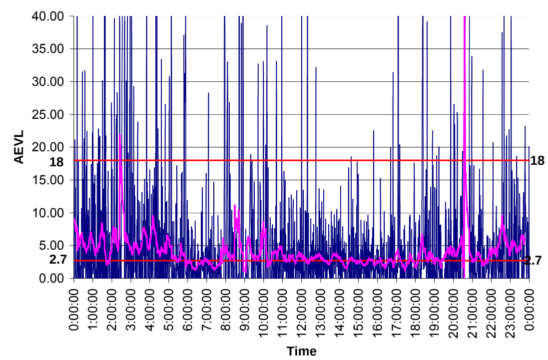
Figure C-21: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 6.4, on Feb 25, 2004



a) Lane 1

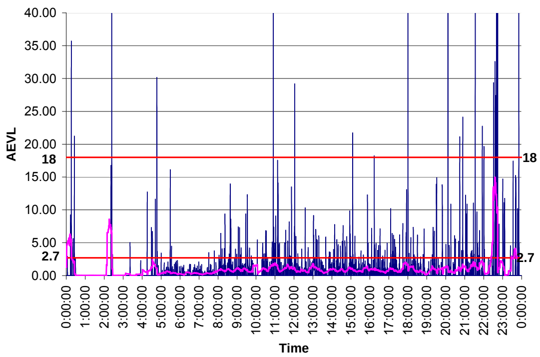


b) Lane 2

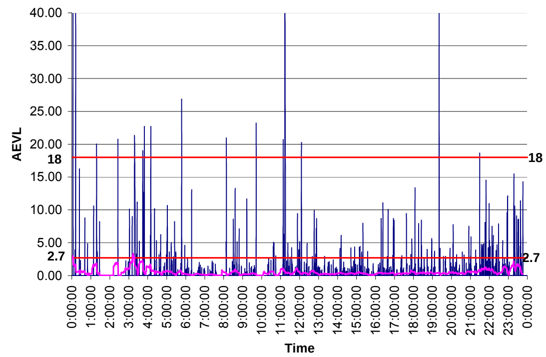


c) Lane 3

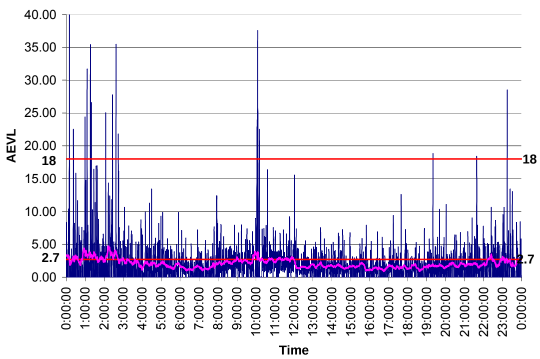
Figure C-22: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 6.9, on Feb 25, 2004



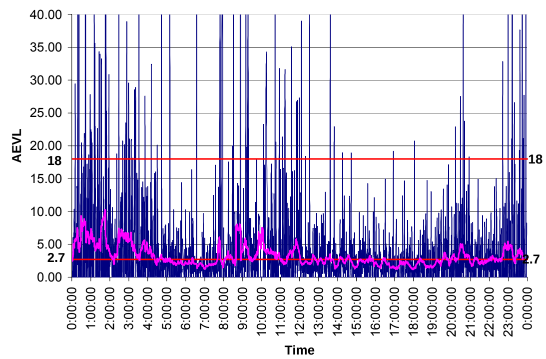
a) Lane 1



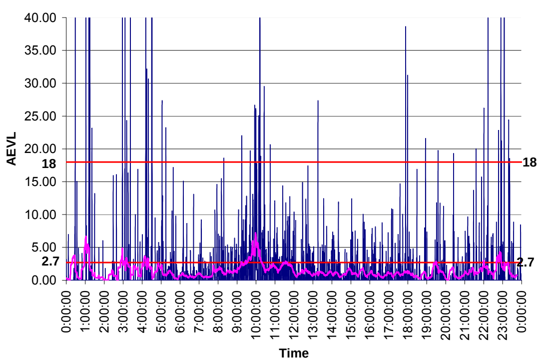
a) Lane 1



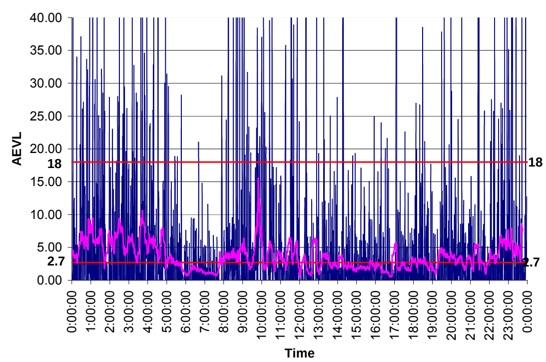
b) Lane 2



b) Lane 2



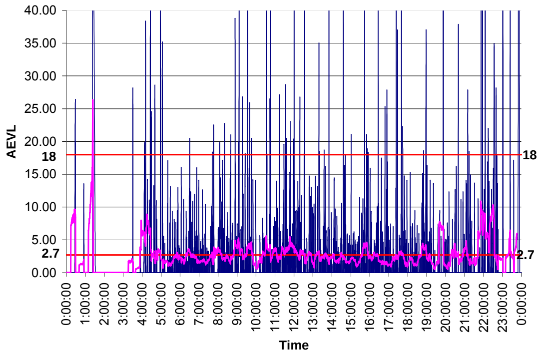
c) Lane 3



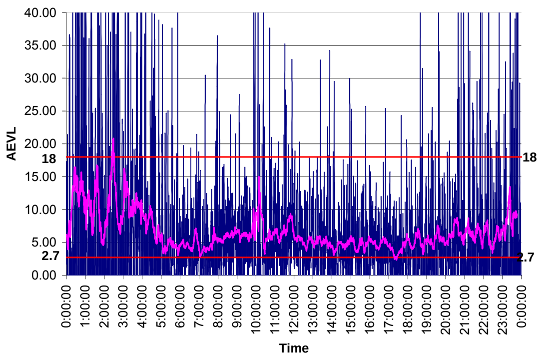
c) Lane 3

Figure C-23: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 7.6, on Feb 25, 2004

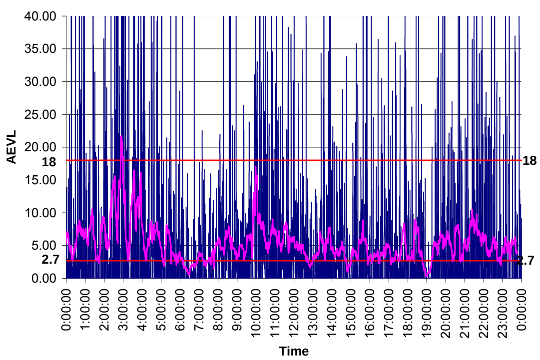
Figure C-24: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 8.7, on Feb 25, 2004



a) Lane 1

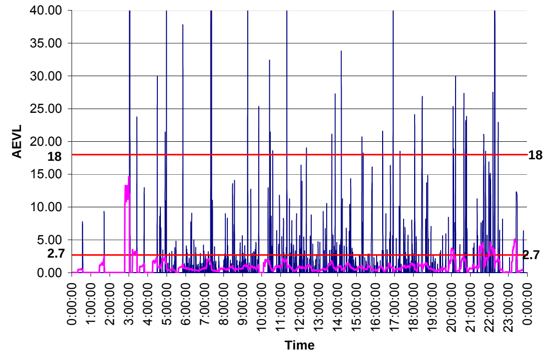


b) Lane 2

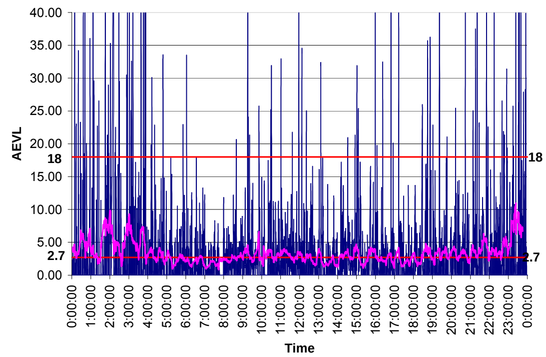


c) Lane 3

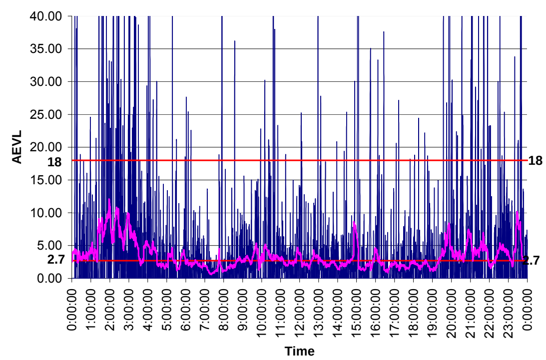
Figure C-25: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 11.7, on Feb 25, 2004



a) Lane 1

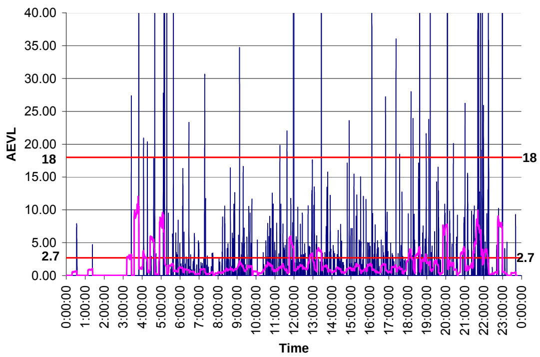


b) Lane 2

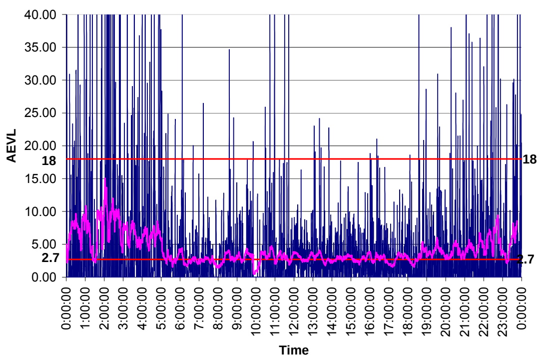


c) Lane 3

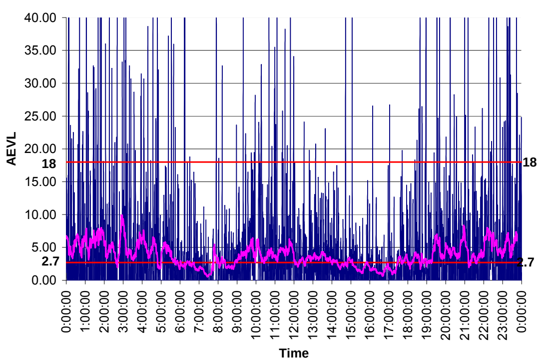
Figure C-26: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 12.5, on Feb 25, 2004



a) Lane 1

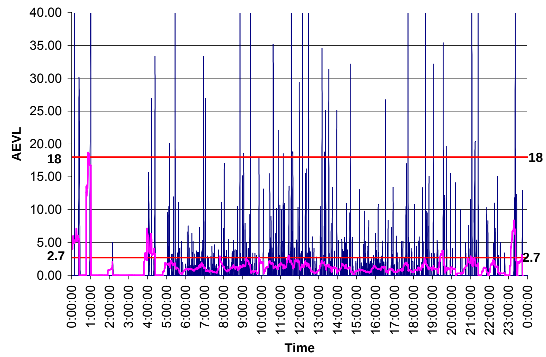


b) Lane 2

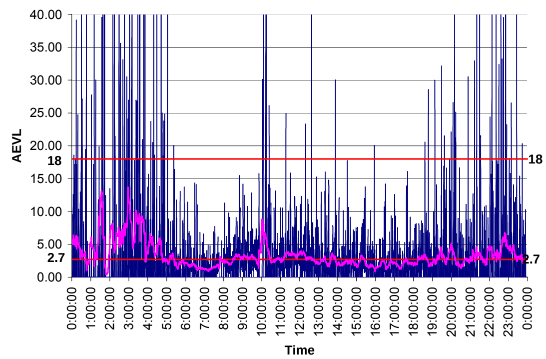


c) Lane 3

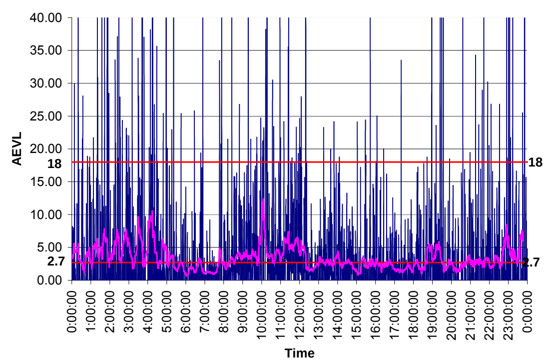
Figure C-27: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 13.5, on Feb 25, 2004



a) Lane 1

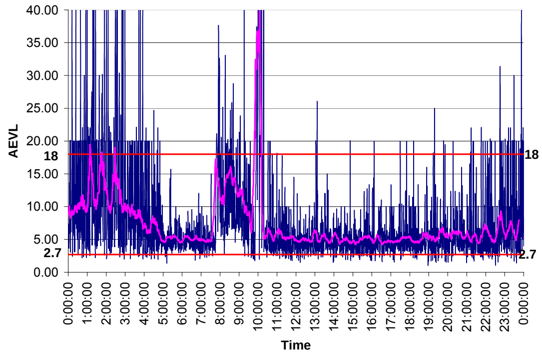


b) Lane 2

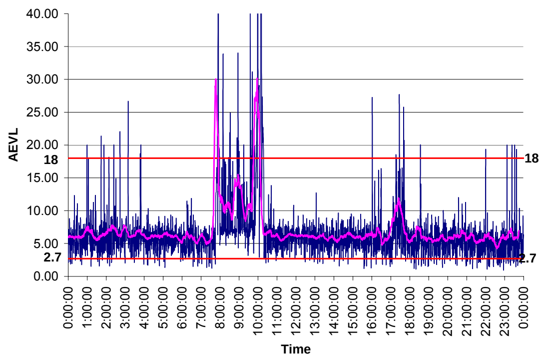


c) Lane 3

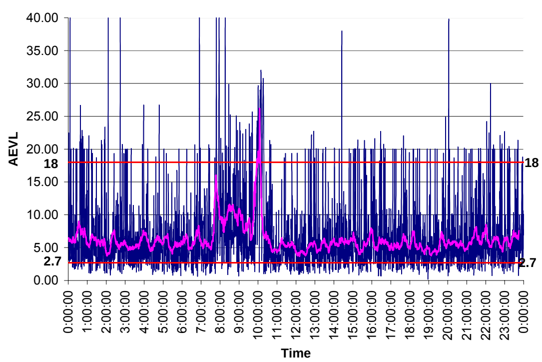
Figure C-28: Average Vehicle Length (m) for microloop on I-80/94, at WB MP 14.9, on Feb 25, 2004



a) Lane 1

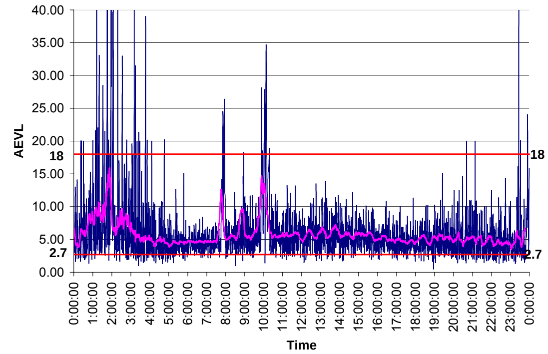


b) Lane 2

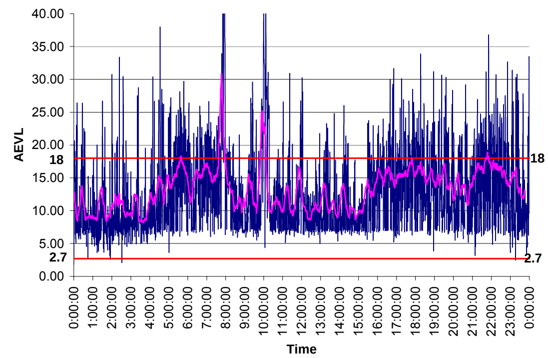


c) Lane 3

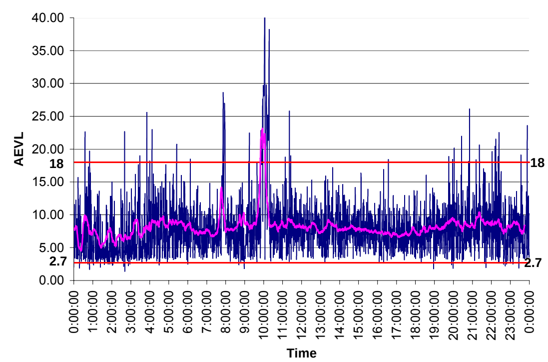
Figure C-29: Average Vehicle Length (m) for RTMS on I-80/94, at WB MP 1.2, on Feb 25, 2004



a) Lane 1

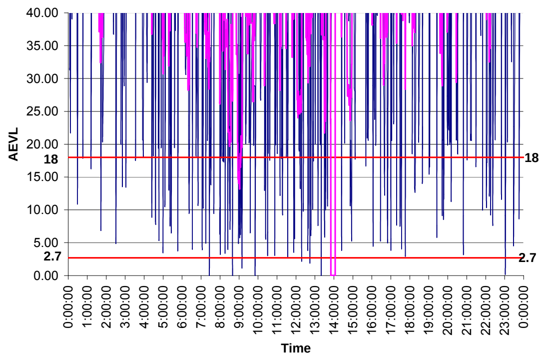


b) Lane 2

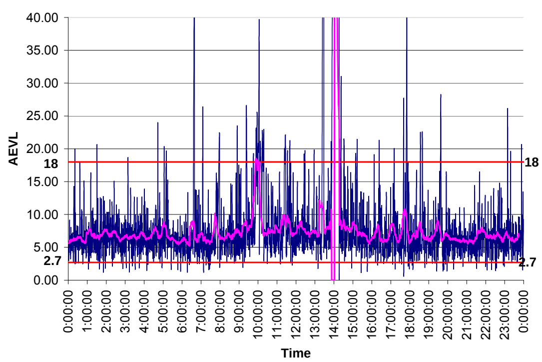


c) Lane 3

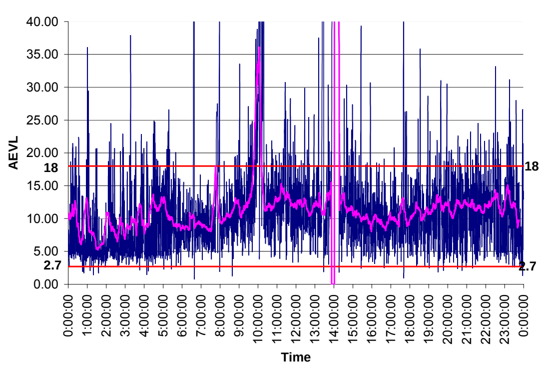
Figure C-30: Average Vehicle Length (m) for RTMS on I-80/94, at WB MP 2.9, on Feb 25, 2004



a) Lane 1
* For lane 1, 67% of the speed data had the very high value of 240 Km/h = 149 mph

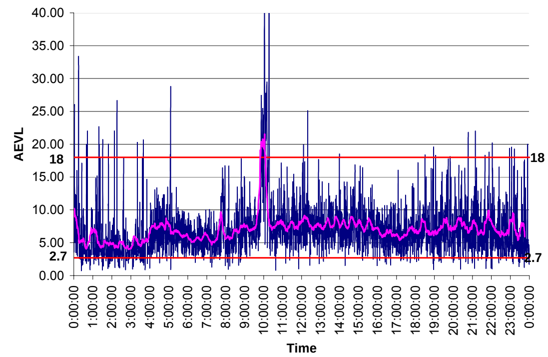


b) Lane 2

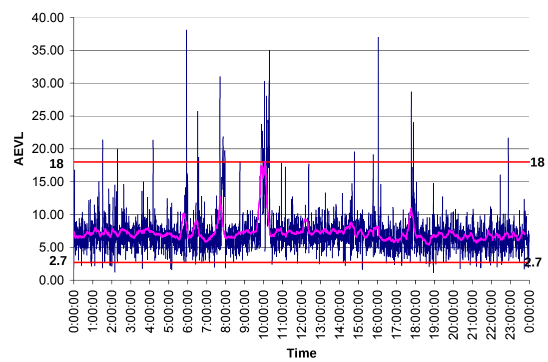


c) Lane 3

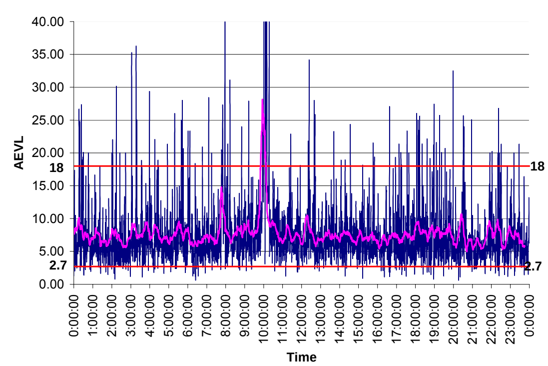
Figure C-31: Average Vehicle Length (m) for RTMS on I-80/94, at WB MP 7.2, on Feb 25, 2004



a) Lane 1

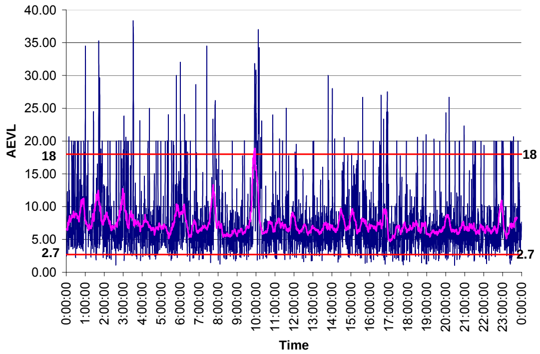


b) Lane 2

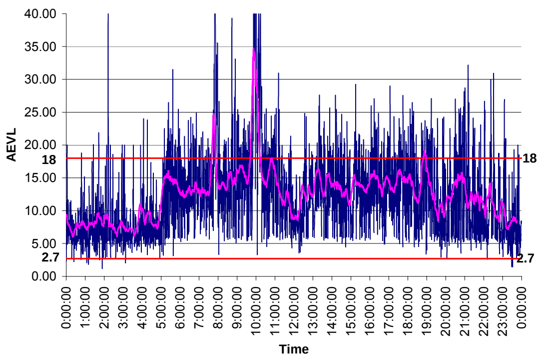


c) Lane 3

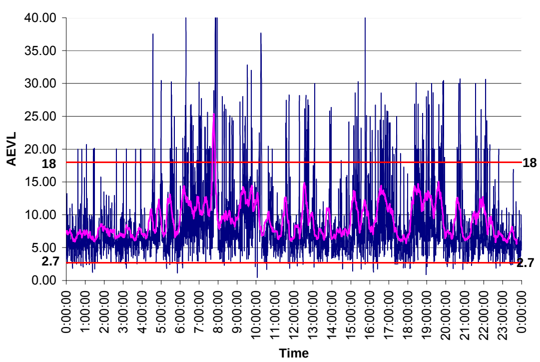
Figure C-32: Average Vehicle Length (m) for RTMS on I-80/94, at WB MP 7.9, on Feb 25, 2004



a) Lane 1



b) Lane 2



c) Lane 3

Figure C-33: Average Vehicle Length (m) for RTMS on I-80/94, at WB MP 14.2, on Feb 25, 2004