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Evaluation of the Accuracy of Traffic Volume Counts Collected by Microwave Sensors

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A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Evaluation of the Accuracy of Traffic Volume Counts Collected by Microwave Sensors

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Over the past few years, the Utah Department of Transportation (UDOT) has developed a system called the Signal Performance Metrics System (SPMS) to evaluate the performance of signalized intersections. This system currently provides data summaries for several performance measures including: 1) Purdue Coordination Diagram, 2) Speed, 3) Approach Volume, 4) Purdue Phase Termination Charts, 5) Split Monitor, 6) Turning Movement Volume Counts, 7) Arrivals on Red, and 8) Approach Delay. There is a need to know the accuracy of the data that are being collected by the Wavetronix SmartSensor Matrix and displayed in the SPMS. The TAC members determined that the following factors would affect the accuracy of radar-based traffic sensors the most: sensor position, number of approach lanes, and volume level. The speed limit factor was added to the study after most of the data collection was completed. The purpose of this research was to collect data at various intersections to determine the accuracy of the data collected by the Wavetronix SmartSensor Matrix.

A Mixed Model Analysis of Variance (ANOVA) was employed to analyze the effects that each factor had on the accuracy of the traffic volume count. A total of 14 tests were performed to examine the effects of the factors on traffic volume count accuracy. The sensor position factor was not found to be a statistically significant factor affecting the accuracy of traffic volume counts. The effect of speed limit on traffic volume count accuracy was determined to be inconclusive due to the lack of samples to be tested. The remaining two factors, volume level and number of approach lanes, were found to have a statistically significant effect on the accuracy of traffic volume counts. Based on these two factors, a matrix was created to meet the needs of UDOT to present accuracy values on the SPMS website. This matrix includes the mean, 95 percent confidence interval of the mean, standard deviation, number of samples, and the minimum number of samples needed.

Keywords: Wavetronix SmartSensor Matrix, volume count accuracy, microwave radar, signal performance metrics system (SPMS), intelligent transportation systems

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1 INTRODUCTION

The Utah Department of Transportation (UDOT) has developed a system called the Signal Performance Metrics System (SPMS) for realizing automatic performance evaluations using the extensive traffic flow data collection infrastructure for signalized intersections. Utah is one of only a few states that use this approach for signalized intersection performance evaluations and the only state that is utilizing microwave radar equipment exclusively for this purpose at the time of this study. The system currently provides data summaries for several performance measures (as of March 30, 2015) including: 1) Purdue Coordination Diagram, 2) Speed, 3) Approach Volume, 4) Purdue Phase Termination Charts, 5) Split Monitor, 6) Turning Movement Volume Counts, 7) Arrivals on Red, and 8) Approach Delay. These performance measures provide signal engineers and others, including the public, immediate access to the data. This allows them to respond quickly to traffic related problems and to collect traffic data for modeling, planning, and other traffic studies. The SPMS can be accessed at http://udottraffic.utah.gov/signalperformancemetrics/.

1.1 Problem Statement

Though the SPMS is operating and functional, UDOT did not have data to prove its accuracy to the users of the SPMS. Hence a study was needed to evaluate its accuracy. The purpose of this research is to conduct a study to calibrate the traffic volume data reported by the SPMS to determine the accuracy of the traffic volume data that the system reports. This is done to give confidence to the users of the data presented in the SPMS.

1.2 Objectives

The first objective of the research was to calibrate lane-by-lane traffic volume counts by Wavetronix's SmartSensor Matrix and determine the accuracy of traffic volume count data provided by the sensor, which is the microwave sensor deployed by UDOT for the SPMS. The second objective was to evaluate the effects of the installation positions of the SmartSensor Matrix on the accuracy of its lane-by-lane volume count data.

1.3 Report Organization

This report is organized into the following chapters: 1) Introduction, 2) Literature Review, 3) Methodology, 4) Results of Statistical Analysis, 5) Application of Results, and 6) Conclusions, followed by a list acronyms, references, and an appendix. Appendix A provides the raw data of this study.

Chapter 1 presents the problem statements and objectives of this research.

Chapter 2 contains a literature review that was conducted to gain a better understanding of automatic traffic flow data collection systems, especially the microwave radar sensors that were evaluated in this research.

Chapter 3 presents the methodology and procedures that were used throughout the course of the research. The data collection and reduction procedures are outlined in this chapter.

Chapter 4 contains the results of statistical analyses based on the factors selected to be evaluated for this study.

Chapter 5 presents recommended application of the results to the SPMS. This section provides the mean accuracy values, as well as the 95 percent confidence intervals of the mean that can be presented in the SPMS to inform the users of the accuracy level of traffic volume counts.

Chapter 6 provides a summary of the study and conclusion of the results of the research. Ideas for future research are also presented.

2 LITERATURE REVIEW

The literature review was conducted to gain a better understanding of roadway traffic sensors, including Wavetronix SmartSensor Matrix, which was used in this study, and the basics of sensing vehicles by radar. This section briefly presents a summary of the literature review, including roadway traffic sensor types, how microwave radar functions, and how the SmartSensor Matrix by Wavetronix functions.

2.1 Roadway Traffic Sensor Types

To help traffic engineers understand traffic patterns and volumes, many types of sensors have been manufactured. These sensors are divided into two categories: non-intrusive and intrusive. They are also known as in-roadway sensors and over-roadway sensors. The definition of a non-intrusives sensor "… is traffic detection sensors that cause minimal disruption to normal traffic operations during installation, operation and maintenance compared to conventional detection methods" (SRF Consulting Group 2010). Examples of these types of sensors include infrared, magnetic, radar, ultrasonic, acoustic, and video imaging sensors (SRF Consulting Group 2010).

On the opposite side of the non-intrusive sensors are intrusive sensors, or traditional sensors, which are defined as "… devices … that involve [the] placement of the sensor technology on top of or into the lane of traffic being monitored" (Skszek 2001). These types of sensors require the closing of traffic lanes and put construction workers in harm's way. Examples of these types of sensors include pneumatic road tube, piezo-electric sensor, magnetic sensor, and inductive loop. Simply put, intrusive sensors require a stop in traffic or a lane closure and non-intrusive sensors are above the roadway surface and don't typically require a stop in traffic or lane closure. Both types of sensors have advantages and disadvantages which will be discussed in the following subsections.

2.1.1 Intrusive Sensors

Intrusive type sensors have been used for many years. Advantages and disadvantages of intrusive sensors including pneumatic road tubes, piezo-electric sensors, magnetic loop sensors, and inductive loop sensors, are discussed in this section with a brief description of each.

2.1.1.1 Pneumatic Road Tubes

Pneumatic road tubes are hollow tubes that are stretched across the surface of a road and can detect a vehicle when air pressure changes inside the tube. They can count the number of axles and measure travel speeds (Skszek 2001). Pneumatic tubes sit on top of the roadway when being used, thus allowing them to be portable. Also, it does not require an expensive structure to be placed on. They are relatively low cost and easy to maintain (Mimbela 2007). However, the fact that pneumatic tubes are portable makes them more susceptible to being stolen or dislodged easily. They also only count the number of axles and not actual vehicles; hence, the average number of axles per vehicle needs to be determined in a separate study. They require technicians to set them up in the roadway, which may require a temporary road closure and create hazardous working conditions for the technicians (Mimbela 2007).

2.1.1.2 Piezo-electric Sensors

Piezo-electric sensors are placed into grooves that are cut into pavement. "The sensors gather data by converting mechanical energy into electrical energy" (Skszek 2001). "This property … allows them to differentiate individual axles with high precision" (Mimbela 2007). Piezo-electric sensors can distinguish vehicle types based on the weight and distance between axles. Like other in-road sensors, however, the biggest drawbacks are that they disrupt traffic during installation and maintenance. They also need to be reinstalled during repaving and other disruptive maintenance, such as utility work. These sensors "…have been known to be sensitive to pavement temperature and vehicle speed" (Mimbela 2007).

2.1.1.3 Magnetic Loop Sensors

Magnetic loop sensors work by detecting disturbances in the normal magnetic field created by the earth. When a metal vehicle passes through a detection zone, it creates a flux in the normal magnetic fields and vehicle presence is detected. An advantage to using magnetic sensors is that they "…are less susceptible than [inductive] loops to stresses of traffic" (Mimbela 2007). The total area of pavement cuts are less than that of induction loops, which allows for longer life of the pavement. Some types of magnetic sensors are able to be used in places where inductive loops cannot be placed (Mimbela 2007). To be able to install these sensors, cuts or coring of pavement needs to occur, which requires lane closures as well as reduces the life of the pavement. Also, these sensors cannot generally detect stopped vehicles and thus cannot be used in presence detection near stop bars at signalized intersections.

2.1.1.4 Inductive Loop Detectors

Inductive loop detectors have been the most common sensor used in traffic management. Their shape and size vary and are embedded in the pavement. Loop detectors are flexible in shape and size; thus, they can be used for various applications such as volume, speed, presence, occupancy, headway, and gap data collection. They are low in cost in comparison to non-intrusive options when only the sensor costs are compared; however, when installation costs are added, the relative costs increase. Loop detectors are placed in the pavement and are subject to the stress of traffic and environmental factors. They are not easily maintained and require lane closures when installing or maintaining (Mimbela 2007).

2.1.2 Non-intrusive Sensors

Non-intrusive sensors are sensors that sit above the roadway surface or away from the travel lanes. They minimally affect traffic during installation and maintenance. Non-intrusive sensors reviewed for this study included video imaging, microwave radar, infrared, and ultrasonic sensors.

2.1.2.1 Video Imaging

Video imaging sensors use a video image and a micro processer to analyze the image. There are two types of methods, trip line and tracking, used in video imaging sensors. “Trip line techniques monitor specific zones on the roadway to detect the presence of a vehicle. Video tracking techniques employ algorithms to identify and track vehicles as they pass through the field of view” (Skszek 2001). Video imaging sensors can perform two jobs with one system. They are able to count vehicles, calculate speeds, and sense vehicle presence, while allowing the engineer to visually see a live feed of what is occurring at intersections equipped with this type of system.

These systems have been constantly improved and tested since their implementation (Mimbela 2007).

Video imaging detectors are susceptible to many different types of environmental factors such as "…day-to-night transition; vehicle/road contrast; water; salt grime; icicles; and cobwebs on camera lens..." (Skszek 2001). For cameras to avoid occlusion, these cameras need to be placed up to 50 feet above the intersection to provide the best results. Along with all the potential problems, these systems are relatively expensive (Skszek 2001).

2.1.2.2 Microwave Radar

Microwave radar uses radio waves to detect objects. The waves that are reflected off of vehicles return back to the sensor, thus knowing that a vehicle is there. Radar sensors can collect various types of data including volume, speed, turning counts, and others. Microwave radars do not use visual imaging and thus are not susceptible to environmental factors such as rain, snow, ice, fog, and others, which are major hindrances to video imaging technologies. "Continuous wave (CW) Doppler radar sensors cannot detect stopped vehicles unless equipped with an auxiliary sensor. CW Doppler radars have been found to perform poorly at intersection[s]…as volume counters" (Mimbela 2007). These sensors are susceptible to occlusion and multipath, which are reflections that energy waves take on returning to the sensor.

2.1.2.3 Infrared Sensors

There are two types of infrared sensors: active and passive. Active infrared sensors emit "… low power infrared energy supplied by laser diodes operating in the near infrared region of the electromagnetic spectrum" (Mimbela 2007). Passive infrared sensors detect energy from the surrounding environment, cars, roadway, etc. Infrared sensors, like other non-intrusive sensors, do not require lane closures during installation and maintenance. In the correct configuration these sensors can gather traffic volume, speed, and vehicle classification data and can be used to control traffic signals using the data collected by themselves. There are many things that emit energy and light. The sun is a large producer of light and energy, thus it could interfere with the infrared sensors. Particles in the air, such as heavy snow, rain, fog, smoke, etc., can absorb or scatter the energy. These effects distort the received image and make it difficult for the sensor to determine what the actual picture is. "If the observer can see the vehicle, there is a high probability the infrared sensor will detect the vehicle" (Mimbela 2007).

2.1.2.4 Ultrasonic Sensors

Ultrasonic sensors use sound energy that is higher than what is audible to humans. These sensors detect reflected energy from passing vehicles and are thus able to calculate vehicle speed, counts, occupancy, and presence (Mimbela 2007). "Installation of ultrasonic sensors does not require an invasive pavement procedure. Also, some models feature multiple lane operation" (Mimbela 2007). Large changes in air temperature and air turbulence can affect the performance of these sensors.

2.1.3 Conclusion

There is no one sensor that is the best and unaffected by all environmental and man-made factors. Each sensor has its own advantages and disadvantages. No one system is perfect, and the performance of each type of sensor varies by manufacturer.

2.2 Microwave Radar

Radar was first developed in the early 1900s and saw its first main use in World War II. Radar, standing for RAdio Detection And Ranging, is defined as “a device for transmitting electromagnetic signals and receiving echoes from objects of interest (i.e., targets) within its volume of coverage" (FHWA 2006). This technology, discovered over a century ago, is still used today, from military warships to police radar guns (Wavetronix 2009a). A basic explanation of radar’s two main components, transmission and receiver will be given in the following subsections.

2.2.1 Transmission

An antenna with a transmitter emits an electromagnetic wave and the energy bounces off objects and then returns back to the receiver to be processed. There are two different types of waveforms that exist: CW and frequency modulated continuous wave (FMCW) radar waveform (FHWA 2006).

2.2.1.1 Continuous Wave (CW) Radar

CW radar sensors rely on the Doppler effect to work: the sensors measure the amount of time that it takes for the energy to travel to a vehicle and back. Since these waves move at the speed of light and are only traveling a few hundred feet, timing of the transmission and reception is very important to acquire good results. These types of radar sensors are able to detect moving vehicles and gather vehicle speeds and counts. Because they rely on the Doppler principle to function, they are not able to detect vehicles that are not moving (Wavetronix 2009a).

2.2.1.2 Frequency Modulated Continuous Wave (FMCW) Radar

FMCW radar sensors work similar to CW radars. They are both based on the time delay to detect objects. There are two distinct differences between the two types of wave forms. The first difference is the way FMWC system emits a pulse that "… consists of a sinusoidal signal that is repeatedly swept from a lower frequency to a higher frequency…" also known as a chirp (Wavetronix 2009a). The second difference is the way the time delay, the time it is emitted to the time it returns, is measured. FMCW sensor "... measures the delay indirectly using frequency rather than time" (Wavetronix 2009a). These types of sensors are able to provide vehicle counts, lane occupancy, speed, and the presence of stopped vehicles.

2.2.2 Receiver

A receiver is a device that detects the transmitted energy that has bounced of an object and returned to the antenna. Once the energy is received, it will be converted to a digital representation and then be processed by an algorithm and become useable data, such as vehicle counts, speed, etc. (Wavetronix 2009a).

2.2.3 Summary

Radar has been around for about a century. There are two basic parts to radar: the transmission and the reception. There are two different wave forms that are used by the transmitter: FMWC and CW. Understanding the differences between these two wave forms enhances the ability to design an experiment.

2.3 Wavetronix SmartSensor Matrix

For this study, the Wavetronix SmartSensor Matrix was used: hence, a brief summary of their functionalities is presented. The Wavetronix SmartSensor Matrix is a microwave radar sensor used in obtaining lane-by-lane traffic counts. An image of this sensor can be seen in Figure 2-1. Radar is the basis on which this sensor works. This sensor has a 90 degree horizontal beam width of view with a 65 degree vertical beam width. An illustration of the vertical beam width can be found in Figure 2-2 (Wavetronix 2015b). The horizontal beam width "…isn't just one radar beam, but a matrix of 16 separate high-definition beams in close proximity to each other. Sixteen separate send/receive antennas generate the beams and measure the distances to all targets in each beam, creating the two-dimensional image known as Radar Vision" (Wavetronix 2015a).

Figure 2-1: Wavetronix SmartSensor Matrix

Figure 2-2: Vertical Beam Width (Wavetronix 2015a)

By using radar, this sensor is able to differentiate lanes where vehicles are counted and count the number of vehicles in each lane. It is also able to detect non-moving vehicles and be used for presence detection. For this sensor to work properly, it must be set up correctly physically and virtually. Further discussion on the sensor mounting location and the virtual set up of lanes and stop bars, and count zones will be presented.

2.3.1 Sensor Mounting Location

For this sensor to work properly, it needs to be positioned in appropriate locations. Wavetronix has identified three locations that are suitable: positions 1, 2, and 3 (see Figure 2-3). Position 1 is located on the back side of the opposing traffic's mast arm. This allows the sensor to be near the lanes of interest. Since this position is close to the lanes, it is considered to be the best for large multi-lane intersections. Position 2 is located on a pole on the far side approach. Position 3 can be located on the adjacent pole or mast arm of the signal. The sensor can also be placed on a light pole or other pole in that general location. These positions are only suggestions, and other locations besides these can be considered. These sensors need to be placed at a minimum of 6 feet from the nearest lane of interest, and it is recommended that it be placed about 20 feet from the ground but has a maximum of 35 feet and minimum of 15 feet from the ground (Wavetronix 2009b).

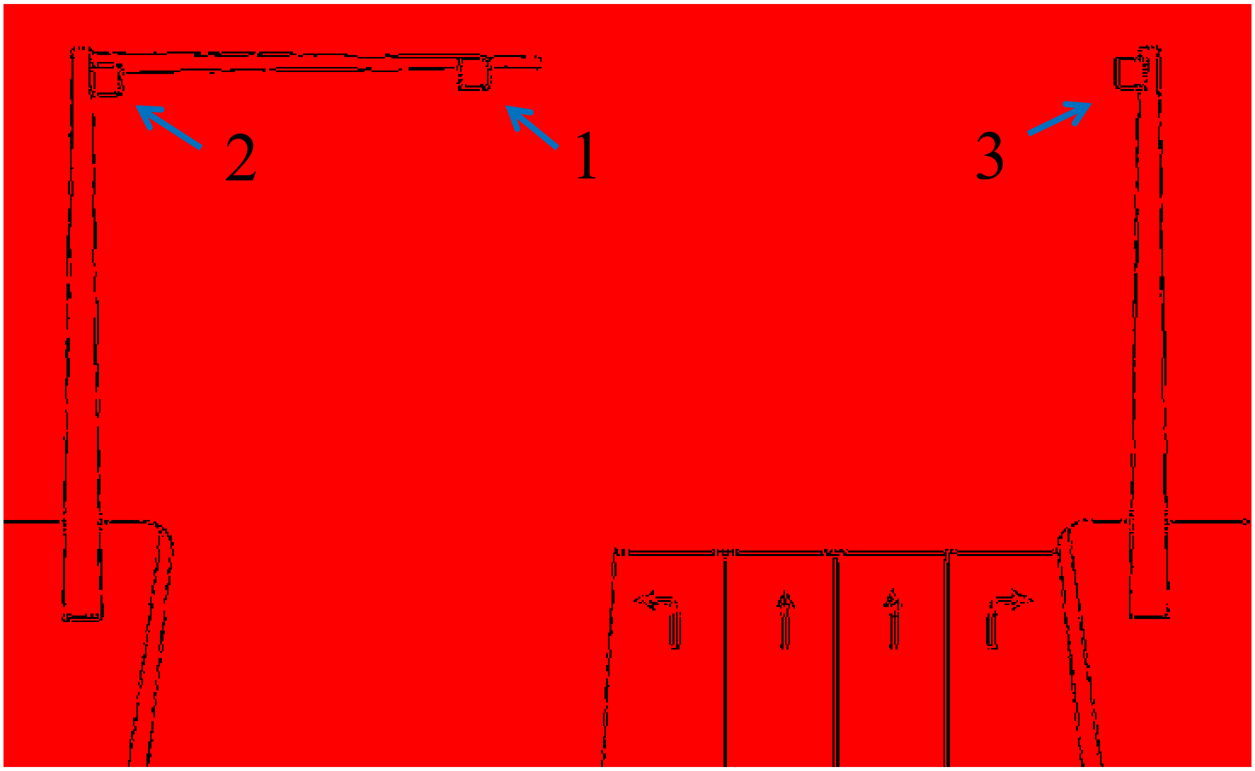


Figure 2-3: Possible Mounting Locations for the SmartSensor Matrix

The physical mounting location is important to avoid occlusion caused by other vehicles. The sensor should be placed nearest the lanes that are most important if at all possible. If the left turn movements are most important, the sensor should be placed on the left side of the intersection of the approaching vehicles. Other important installation information to remember is that the radar has a range of 140 feet and fans out to cover a 90-degree angle from the sensor (Wavetronix 2015b). Thus the resulting shape of the sensor field takes the appearance of a “fan-shaped” area (see Figure 2-4). It is important that vehicles entering the SmartSensor Matrix’s field of view do so on the arc rather than the straight sides. A vehicle needs to be tracked by the SmartSensor

Matrix before the count zone placed at the stop bar; otherwise, the algorithm thinks the detection by the SmartSensor Matrix was a ghost, or false call, rather than an actual vehicle.

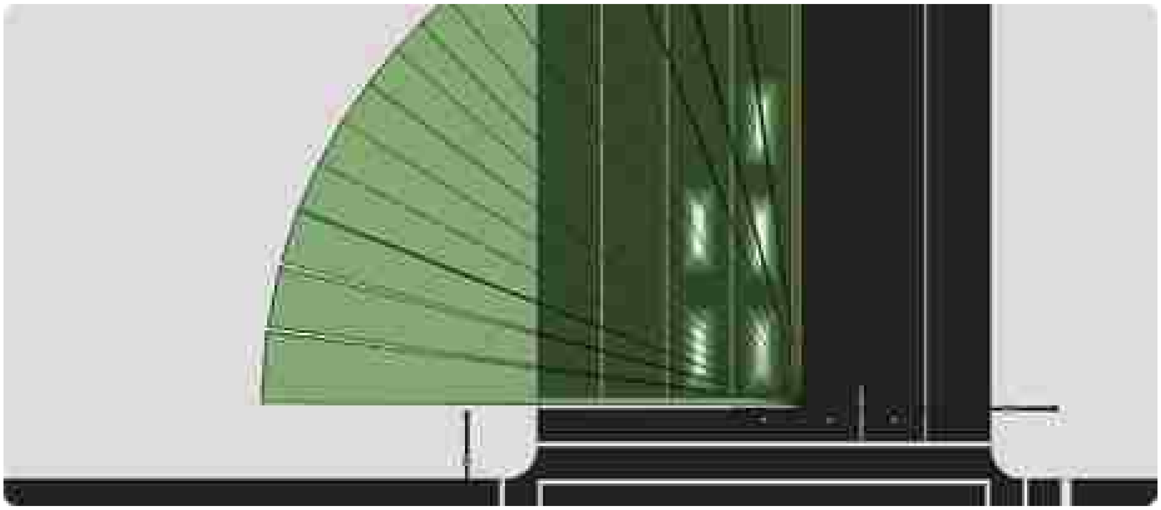


Figure 2-4: The Radar Beam Width of the SmartSensor Matrix Sensor (Wavetronix 2015a)

2.3.2 Lanes and Stop Bar

Once the sensor has been mounted correctly, the lanes and stop bars need to be placed into the sensor firmware. This can be drawn in using the SmartSensor Manager Matrix (SSMM) software while the laptop is connected locally to the sensor. During set up, the sensor displays white dots to indicate the location of vehicles. These white dots can help the user determine where to draw the lanes in the software. Performance is best when the vehicles enter the sensor view on the arc or, in terms of the baseball diamond, the outfield rather than the foul lines (Wavetronix 2009b).

2.3.3 Count Zones

A count zone is an area that is drawn into the firmware to indicate the location to count vehicles as they pass through. This area commonly starts at the stop bar of an intersection and continues into the intersection. These count zones can be either entered in manually or automatically. The length and width can be adjusted to meet the needs for the user (Skszek 2001).

2.3.4 Summary

The microwave radar sensor that was used in this study was the Wavetronix SmartSensor Matrix. This sensor was designed to capture turning counts at intersections. There are three typical installation positions that are recommended for this sensor: position 1, position 2, and position 3. There are also recommended ways to draw the detection zones that count the vehicles.

2.4 Chapter Summary

There are many different types of traffic sensors available, both intrusive and non-intrusive. One type of traffic sensor is radar based. Radar works off of the Doppler principle to locate and detect vehicles to gather data. The Wavetronix SmartSensor Matrix is a radar traffic sensor that is used in this study and is capable of vehicle detection through FMCW radar. Through proper care in installation following the minimum and maximum height requirements, this traffic sensor will properly function.

3 METHODOLOGY

In this study, Wavetronix SmartSensor Matrix with firmware version 1.3.2 was used to test the accuracy of turning volume counts by microwave radar. The SmartSensor Matrix is a presence detection microwave radar sensor. Through the presence detection, the SmartSensor Matrix is able to count vehicles in different lanes separately. This study evaluated locations that were set up to meet the manufacturer's specifications. Thus the results can only be applied back to locations where the sensors have been set up likewise. This chapter identifies and discusses the factors evaluated in the study, sample size determination, site selection, accuracy definition, data collection, sample data collection, data reduction, and accuracy check.

3.1 Factors

The intersection performance criteria to be tested in this project were determined by the Technical Advisory Committee (TAC) consisting of UDOT and Wavetronix representatives and the Brigham Young University (BYU) research team. It was determined that all three alternate installation positions of the Wavetronix SmartSensor Matrix that were used at the time of study would be tested for accuracy. It was also decided that there would be two other factors that would be tested to determine if they had any effect on the traffic volume count accuracy of the SmartSensor Matrix; they were intersection size, in terms of the number of approach lanes per direction, and demand level, in terms of the volume of traffic expressed in average number of vehicles per hour per lane (veh/hr/ln). The volume of traffic was divided into three levels: low, medium, and high. The thresholds for these levels were not decided until preliminary data collection was performed. Each of these factors is discussed later in this chapter and how they were divided into factor combinations.

3.1.1 Sensor Position

The first factor looked at was the sensor position. As previously mentioned, there are three typical installation positions that are recommended by Wavetronix (see Figure 2-3). The first group is called sensor position 1 in this study, which is the most commonly used position by UDOT and also recommended as the primary location by Wavetronix. Position 2 is group 2 and position 3 becomes group 3, as illustrated in Table 3-1, for this study. These alternate installation locations were discussed in section 2.3.1.

3.1.2 Number of Approach Lanes

The next factor to be analyzed was the number of lanes in an approach. This is expressed by the number of lanes that a single approach contains. This is an important factor because it will be able to determine if the size of an intersection affects the performance of the traffic count accuracy of the SmartSensor Matrix.

3.1.3 Traffic Volume Level

The last factor that was investigated is traffic volume level. It was determined that the total volume of traffic would be divided by the total number of lanes to give a volume level per hour per lane. This was done to limit the amount of factors included in this study. The thresholds or cutoffs of each level of traffic were later determined after observing and collecting data. The threshold between low and medium was set to 100 veh/hr/ln. The threshold between medium and high was set to 250 veh/hr/ln. These numbers were chosen after about 30 traffic volume counts had been completed at different volume levels. Using the UDOT SPMS website (UDOT 2015), distribution of traffic volumes within a day was observed to determine when the lowest and highest volume of traffic occurred. Each intersection was counted at three separate time periods with three different volume levels. The volume levels were not consistent across all the intersections. Once there were a sufficient number of samples collected at various traffic volume levels, using engineering judgment, the samples were divided into three volume levels while attempting to make each of the three volume levels roughly equal in sample size. The thresholds were changed in increments of 25 veh/hr/ln at a time and then counted to see how many remained in each threshold. Using this procedure, the threshold for each volume level was determined to be less than or equal to100 veh/hr/ln for a low volume count, between 101 and 250 veh/hr/ln for a mid volume level, and greater than 250 veh/hr/ln for a high volume level.

Within each sensor installation location, volume of traffic and number of approach lanes combinations needed to be observed. Each installation location needed to have all three levels of traffic volume and all number of approach lanes. With this understanding, combinations in each installation position were created, as shown in Table 3-1.

Group 1, as seen in Table 3-1, has the highest number of approach lane combinations, from two lanes to as many as six lanes in an approach. Under each number of approach lanes, there are three levels of traffic volumes, low, medium, and high, for a total of 15 combinations. Groups 2 and 3 both had two, three, and four lanes in an approach. Each of these approaches had the same levels of traffic volumes as group 1: low, medium, and high. Both groups 2 and 3 had nine combinations each, giving a total of 33 combinations, including group 1, for data collection in this project. It was determined that each combination's target number of samples would be seven after preliminary estimation, as discussed in section 3.2. All three of these factors were evaluated for their impact on traffic volume count accuracy.

Table 3-1: Possible Combinations for Analysis Groups 1, 2, and 3

Group 1					
	Matrix Sensor Position 1				
	Number of Approach Lanes				
	2	3	4	5	6
Traffic Volume	Low Medium High	Low Medium High	Low Medium High	Low Medium High	Low Medium High

Group 2			
	Matrix Sensor Position 2		
	Number of Approach Lanes		
	2	3	4
Traffic Volume	Low Medium High	Low Medium High	Low Medium High

Group 3			
	Matrix Sensor Position 3		
	Number of Approach Lanes		
	2	3	4
Traffic Volume	Low Medium High	Low Medium High	Low Medium High

3.2 Determining Sample Size

Before the site locations could be selected, the number of samples required to meet the confidence level criterion needed to be determined for each factor combination. Using Equation 3-1, the number of samples that needed to be collected for each factor combination was determined (Roess et. al 2009).

$$N = \frac{S^2 * Z^2}{E^2} \tag{3-1}$$

Before the calculation could occur, there were three variables in which assumptions needed to occur, which were z-score, precision, and standard deviation. It was decided that a z-score (*Z*) of 1.96 would be used, representing a 95 percent confidence level. The standard error of the mean (*E*) and standard deviation (*S*) were determined after the preliminary data collection was performed. Based on the preliminary data collection at University Avenue and University Parkway, it was determined that the standard deviation was approximately 6.5 percent. The permitted error in volume count accuracy was then determined to be between 5 and 10 percent based on comments from the UDOT TAC members. Based on these assumptions, the number of samples needed for each combination of factor levels was 7 if *E* was equal to 5 percent, 3 if *E* was equal to 7.5 percent, and 2 if *E* was equal to 10 percent. Based on these calculated values, it was decided to use seven samples for each combination of factors to start with. The final check on the number of samples needed will be presented in Chapter 5.

3.3 Site Selection

Study sites were chosen from a list of intersections that are equipped with the SmartSensor Matrix. The initial list of study sites was created by the TAC members from UDOT. This list of intersections consisted of 18 intersections across two counties in Utah: Salt Lake and Utah counties. This original list of intersections only provided the locations and did not provide the sensor position or number of lanes in an approach. This data had to be collected visually by the BYU research team. Many of the intersections in this list were in Utah County, a central location to the research team. The remaining intersections were located in Salt Lake County. Once the initial list of sites was chosen, a team from UDOT and Wavetronix traveled to each site to complete a quality control and quality assurance (QC/QA) task. It was the responsibility of the team to ensure that each sensor was set up and positioned to the manufacturer's standards. The sensors needed to be aimed correctly and the virtual count zones needed to be drawn and placed in the correct locations. Slight modifications to the virtual count zones were completed to allow the sensor to count vehicles most accurately. The team of UDOT and Wavetronix would do a quick evaluation of the sensor to determine if the sensor was set up as best as possible. During the quick evaluation, the team aimed for an accuracy rate of approximately 90 percent. The initial list of sites from the UDOT TAC members did not provide enough data points in all of the groups; thus more intersections had to be investigated and chosen for data collection.

The second list of signalized intersections equipped with SmartSensor Matrix was created by the BYU research team. Together with the first list, this list of intersections provided enough study sites to conduct a rigorous statistical analysis for each of the 33 factor combinations. The list from which the intersections were chosen did not state the sensor positions or the number of lanes each approach has. These two pieces of information needed to be collected visually before the second set of study sites could be chosen. This was done by first examining images from Google Earth street view (Google 2015) to verify that the sensors existed and then to determine the sensor positions. Not all potential study sites had up-to-date images on Google's street view, so visual confirmation was needed to confirm sensor position and the number of approach lanes in each direction. The visual confirmation was done by onsite visits or by using the UDOT Closed Circuit Television (CCTV) system, which is accessible from the BYU Transportation Lab.

These data were compiled into a spreadsheet and intersections were chosen based on the relevance to data requirements. Sites that were located closer to the BYU research team and/or had UDOT CCTV cameras were given priority in the selection process. Like the initial list of study sites, the second list had a QC/QA task completed. A team from UDOT and Wavetronix traveled to each site to complete a QC/QA task before data collection. When UDOT and Wavetronix completed their portion of the QC/QA task, the BYU research team was given the green light to start data collection at the sites.

3.4 Determining Accuracy

To be able to compare the accuracy of the volume counts to other intersections, it was important to have a consistent method to use. It was determined that using the percent of volume counted, defined as the sensor volume counts divided by the manual volume counts as "accuracy," would fill the need of this project. Another reason that this method was chosen was that the volumes would be different between each intersection, thus making a direct comparison of volume counts between intersections not practical.

3.5 Data Collection

After the list of study sites was completed, two types of data were needed. The first type was traffic volume counts done by the BYU research team (i.e., "ground-truth" volume counts), and the second was the volume counts reported by the sensor, called "Hi-res" data by UDOT engineers.

The traffic volume counts were done either on site or by using the UDOT CCTV system. In the Transportation Lab located in the Clyde Building of BYU, the research team recorded traffic flow at intersections that were equipped with a camera and displayed it on a monitor in the transportation lab to be used as backup data and for verification. The lane-by-lane counts were completed manually using a JAMAR traffic counter for both on-site and the video recordings. A JAMAR counter was chosen because it automatically keeps track of the data summary intervals and time. It also allowed an easy, fast, and simple way to download the data into a spreadsheet. Each intersection was counted for a total of 1 hour with 5 minute intervals. Vehicle classifications were also tracked to find possible explanations for sensor error. The start times for each count were also logged to the nearest second. This was very important to ensure that the Hi-res data could be compared to the manual counts correctly. This counting method will be explained further in section 3.5.1. This method of counting was determined by the BYU research team to be the most accurate and consistent for this study.

The method that was used to ensure clocks between the manual counts and the Hi-res data were synced up was to use the time the signal turned green in the through direction of the approach in which traffic data were to be collected. It is important to have a consistent and accurate way to sync-up the start times between the manual counts and the Hi-res data. This method was chosen over the "gap-between-vehicle" method because the start of green phases is logged in the Hi-res data, thus making it easy to know when the green phase begins. The "gap-between-vehicle" method looks at the time gap between vehicles. The research team would have to record the time that passed between two vehicles with this method. The gap method had a few problems with it. The first problem was that there could be multiple vehicles with the same time gap, thus making it hard to know exactly with which vehicle the research team started counting vehicles. Another potential problem was that if the sensor did not detect the vehicle that the research team used to start counting, there would be no log of that vehicle in the Hi-res data, making it impossible to know when the count started.

The BYU research team members were instructed to start all counts at the beginning of the green phase of the through movement. If this was not possible, the team members were to note which green phase they started on. Each member of the data collection team was able to download the same clock application onto similar smart phones. This application included seconds in the time. This limits the amount of time difference between different team members collecting the data, thus allowing consistency throughout the project. Consistency was an important aspect of the ground-truth data collection and reduction process of this study. Further explanation on the lane-by-lane approach volumes will occur in the following subsection.

3.5.1 Lane by Lane Approach Volumes

When collecting data in the field, two different methods were used, as discussed in the previous section. The first method was on site, while the second was using the UDOT CCTV system. Further discussion on both of these methods is given in the following subsections.

3.5.1.1 On-Site Data Collection Method

The first and preferred method used was physically being at the intersection counting approach volumes (see Figure 3-1). This method was preferred because it allowed the team to learn and see what is actually happening at a particular intersection. It allows the ability to hear and see cars before and after they arrive at the stop bar. This was important at intersections that were high speed where vehicles can only be seen for an instant on the camera or where large trucks cause occlusion of smaller vehicles. An on-site count provided the ability to see before and after the stop bar as well as under or through large trucks to obtain the most accurate counts.

Figure 3-1: On-site Data Collection

3.5.1.2 CCTV Data Collection Method

The second method was to either watch the UDOT CCTV live broadcasting or a recording of the live feed to watch later (see Figure 3-2). When recording the live feed from the CCTV system, the BYU team used a personal digital video camera in order to get a time stamp on the video. This method was extremely helpful for intersections that had low volume levels either early in the mornings or late at nights. The CCTV system allowed the team to not have to wake up and travel before 6:00AM or after midnight on a daily basis. The recorded video also allowed the team to go back and investigate possible errors in volume counting that might have occurred. The height of the camera was also advantageous at most intersections. Many of the cameras were positioned high above the intersection, limiting the occurrence of occlusion.

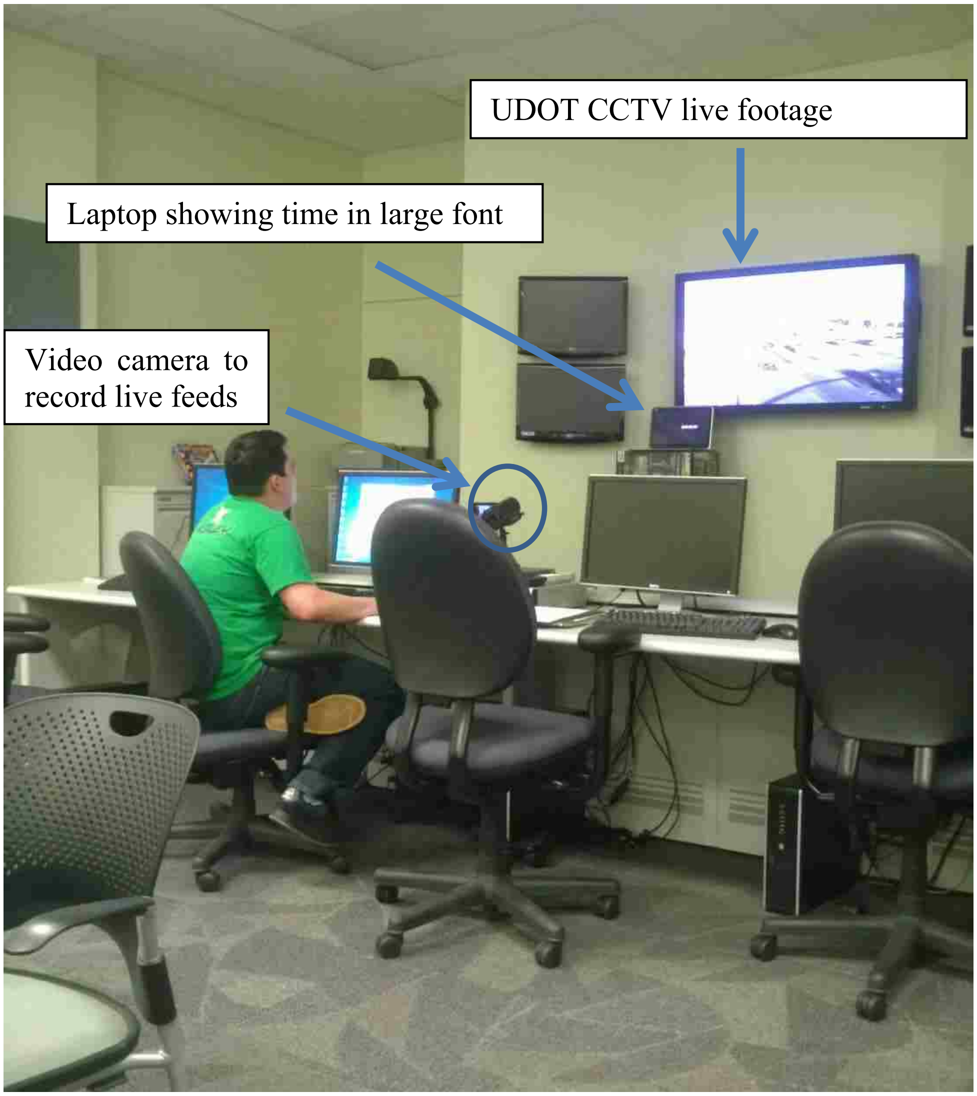


Figure 3-2: Data collection via UDOT CCTV

However, the use of technology had a few problems to work through. On occasion, the cameras would stop working, thus making a count unusable. In these instances, if the camera would consistently stop working, the team would have to travel to the intersection to obtain the counts manually. Another problem that had to be worked through was that some of the CCTV cameras were set up with an "auto-home" function. This occurs when the camera has a default direction it is set to, and after 30 minutes or other predetermined amount of time of non-use it will automatically rotate to the default direction. Working closely with UDOT, this issue was easily resolved. Another problem that occurred on occasion was when the camera would be inadvertently turned by UDOT employees to a different direction while recording the video.

When using the camera to complete traffic counts, it was important to set up the UDOT cameras correctly. This required that the camera be facing the correct direction. This was sometimes challenging since the surrounding buildings and area were unfamiliar to the BYU research team. When using the camera to record UDOT CCTV video feed, a time stamp needed to be on the video to know when the video was recorded. The video feed did not provide a time stamp, so a laptop was used to display the current time (see Figure 3-2). The BYU team would use a video camera to record both the live video feed from the UDOT CCTV cameras and the time that was displayed on the laptop, down to the second. This method was determined to sufficiently serve the needs of this project.

When collecting volume counts, it was important to have a consistent way to count vehicles. It was determined that a vehicle would be counted by the research team when the rear tire of the vehicle was on or crossed the stop bar, as illustrated in Figure 3-3. This distinction was important in instances when a vehicle would partially cross a stop bar during a red light and would not pass through the intersection.

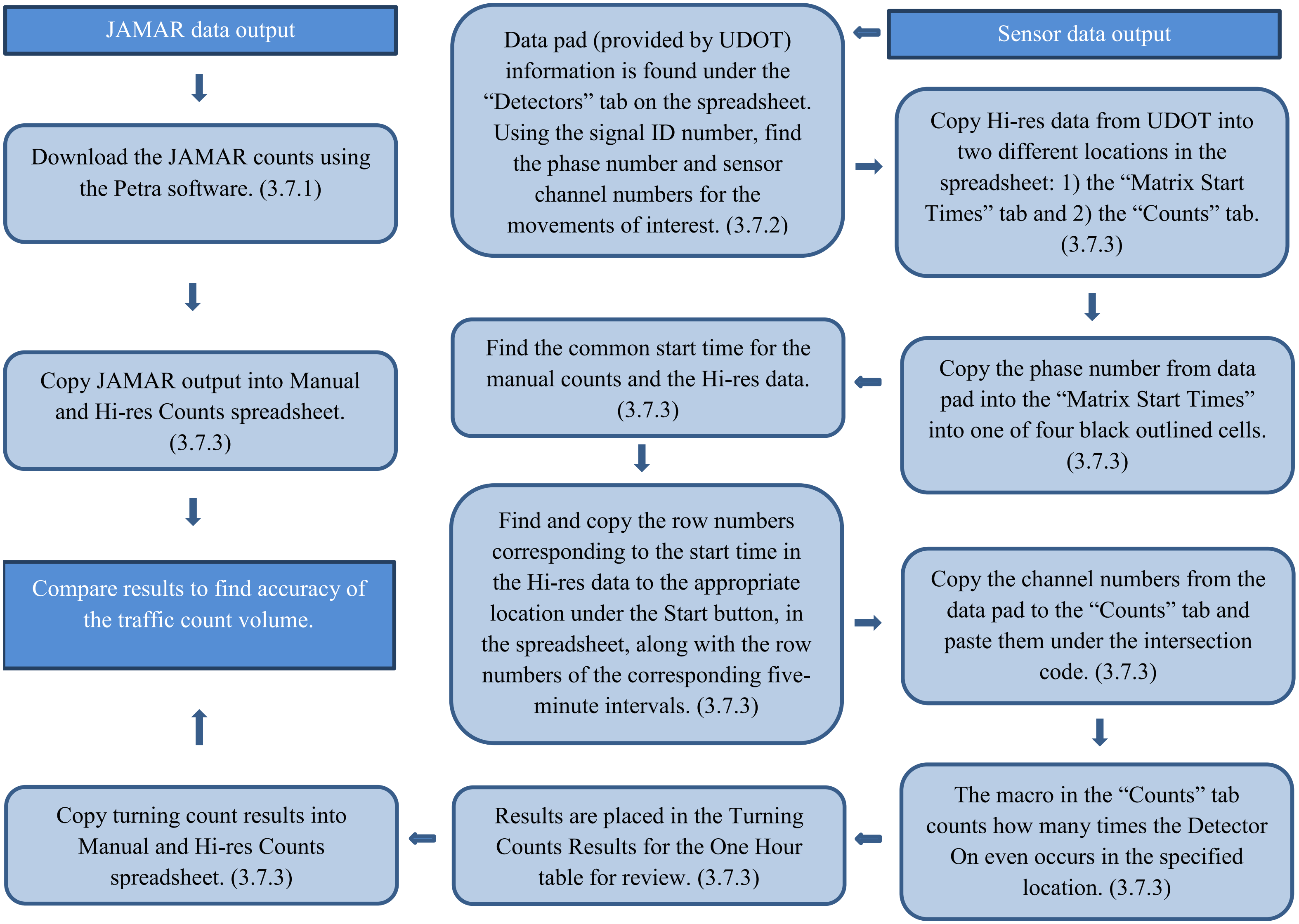
3.6 Sample Data Collection

Before full scale data collection began, a small scale sample data collection was performed. The purpose of this sample data collection was for the BYU team to practice the method that was to be implemented, work out any problems that may arise, and foresee potential problems. The test site chosen was the intersection at University Avenue and University Parkway in Provo, Utah. This intersection has four approaches with four lanes in each approach. Only the northbound direction was used in the sample data collection. The sample data collection was run for 30 minutes. The team started data collection on the green phase of the through movement and counted the vehicles that crossed the stop bar using the JAMAR counter. This allowed the team to get familiar with the technology and methods to be used in this project.

Figure 3-3: Vehicle Counting Technique

3.7 Data Reduction

Data reduction took place after both the manual counts and the Hi-res sensor data had been acquired. The data reduction took place at the Transportation Lab at BYU. A brief discussion about JAMAR data output, the sensor data output, and data reduction of the sensor data output is presented in the following subsections. A flow chart has been provided to aid the reader in the flow of the data reduction. The flow chart is found in .



JAMAR data output

Download the JAMAR counts using the Petra software. (3.7.1)

Copy JAMAR output into Manual and Hi-res Counts spreadsheet. (3.7.3)

Compare results to find accuracy of the traffic count volume.

Copy turning count results into Manual and Hi-res Counts spreadsheet. (3.7.3)

Data pad (provided by UDOT) information is found under the “Detectors” tab on the spreadsheet. Using the signal ID number, find the phase number and sensor channel numbers for the movements of interest. (3.7.2)

Find the common start time for the manual counts and the Hi-res data. (3.7.3)

Find and copy the row numbers corresponding to the start time in the Hi-res data to the appropriate location under the Start button, in the spreadsheet, along with the row numbers of the corresponding five-minute intervals. (3.7.3)

Results are placed in the Turning Counts Results for the One Hour table for review. (3.7.3)

Sensor data output

Copy Hi-res data from UDOT into two different locations in the spreadsheet: 1) the “Matrix Start Times” tab and 2) the “Counts” tab. (3.7.3)

Copy the phase number from data pad into the “Matrix Start Times” into one of four black outlined cells. (3.7.3)

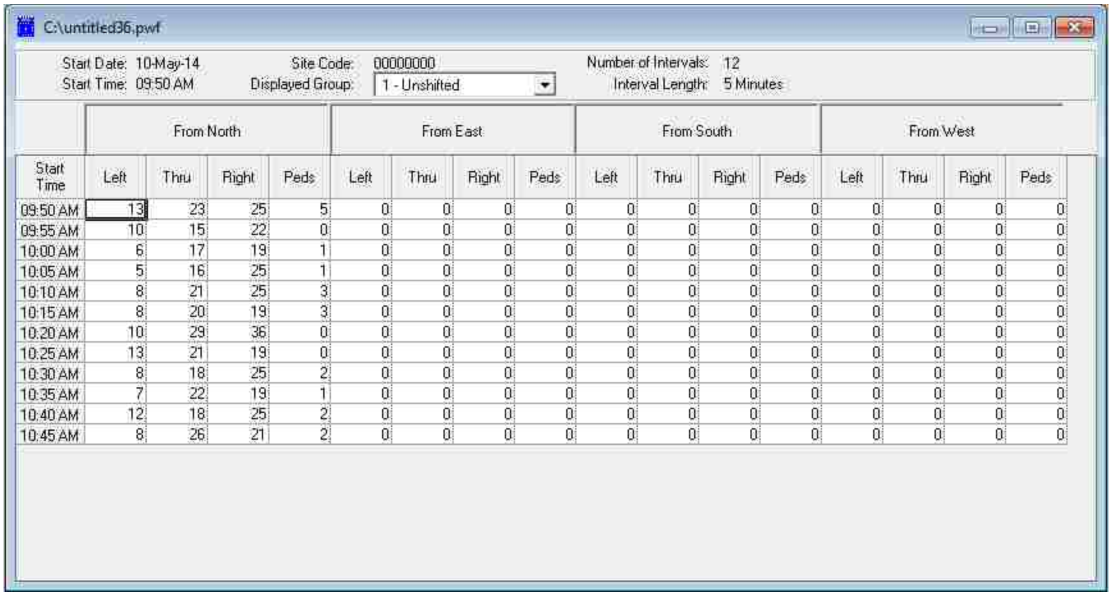
Copy the channel numbers from the data pad to the “Counts” tab and paste them under the intersection code. (3.7.3)

The macro in the “Counts” tab counts how many times the Detector On even occurs in the specified location. (3.7.3)

Figure 3-4: Data Reduction Flow Chart

3.7.1 JAMAR Counters Data Output

The manual counts were conducted using a JAMAR counter. The completed counts were then downloaded using the Petra software (see Figure 3-5) (JAMAR Technologies, Inc. 2015). The downloaded data were then copied to the manual and Hi-res counts spreadsheet to be saved and later to be compared to the Hi-res data (see Figure 3-6). Each spreadsheet was labeled using the intersection name. The date and time of each manual and Hi-res count were also recorded for future reference.



Start Date: 10-May-14
Start Time: 09:50 AM
Site Code: 00000000
Displayed Group: 1 - Unshifted
Number of Intervals: 12
Interval Length: 5 Minutes

	From North				From East				From South				From West			
Start Time	Left	Thru	Right	Peds	Left	Thru	Right	Peds	Left	Thru	Right	Peds	Left	Thru	Right	Peds
09:50 AM	13	23	25	5	0	0	0	0	0	0	0	0	0	0	0	0
09:55 AM	10	15	22	0	0	0	0	0	0	0	0	0	0	0	0	0
10:00 AM	6	17	19	1	0	0	0	0	0	0	0	0	0	0	0	0
10:05 AM	5	16	25	1	0	0	0	0	0	0	0	0	0	0	0	0
10:10 AM	8	21	25	3	0	0	0	0	0	0	0	0	0	0	0	0
10:15 AM	8	20	19	3	0	0	0	0	0	0	0	0	0	0	0	0
10:20 AM	10	29	36	0	0	0	0	0	0	0	0	0	0	0	0	0
10:25 AM	13	21	19	0	0	0	0	0	0	0	0	0	0	0	0	0
10:30 AM	8	18	25	2	0	0	0	0	0	0	0	0	0	0	0	0
10:35 AM	7	22	19	1	0	0	0	0	0	0	0	0	0	0	0	0
10:40 AM	12	18	25	2	0	0	0	0	0	0	0	0	0	0	0	0
10:45 AM	8	26	21	2	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3-5: Sample JAMAR Counters Output

3.7.2 Sensor Data Output

Data reduction is an important step for comparing the manual counts with the sensor counts. Before data reduction can take place, an understanding of the sensor data output is necessary.

The data that are received by a UDOT traffic server come from the traffic controller. The controller logs every event that takes place at its intersection and pushes the data out to the UDOT traffic data server. The raw data have four columns (see Figure 3-7). Each column has a unique meaning that will be discussed further in the following paragraphs. Once the traffic controller logs each event, it then will push the logged data out to the UDOT server. These data are stored on the UDOT server for future use. A UDOT TAC member sent the raw Hi-res data to the BYU research team.

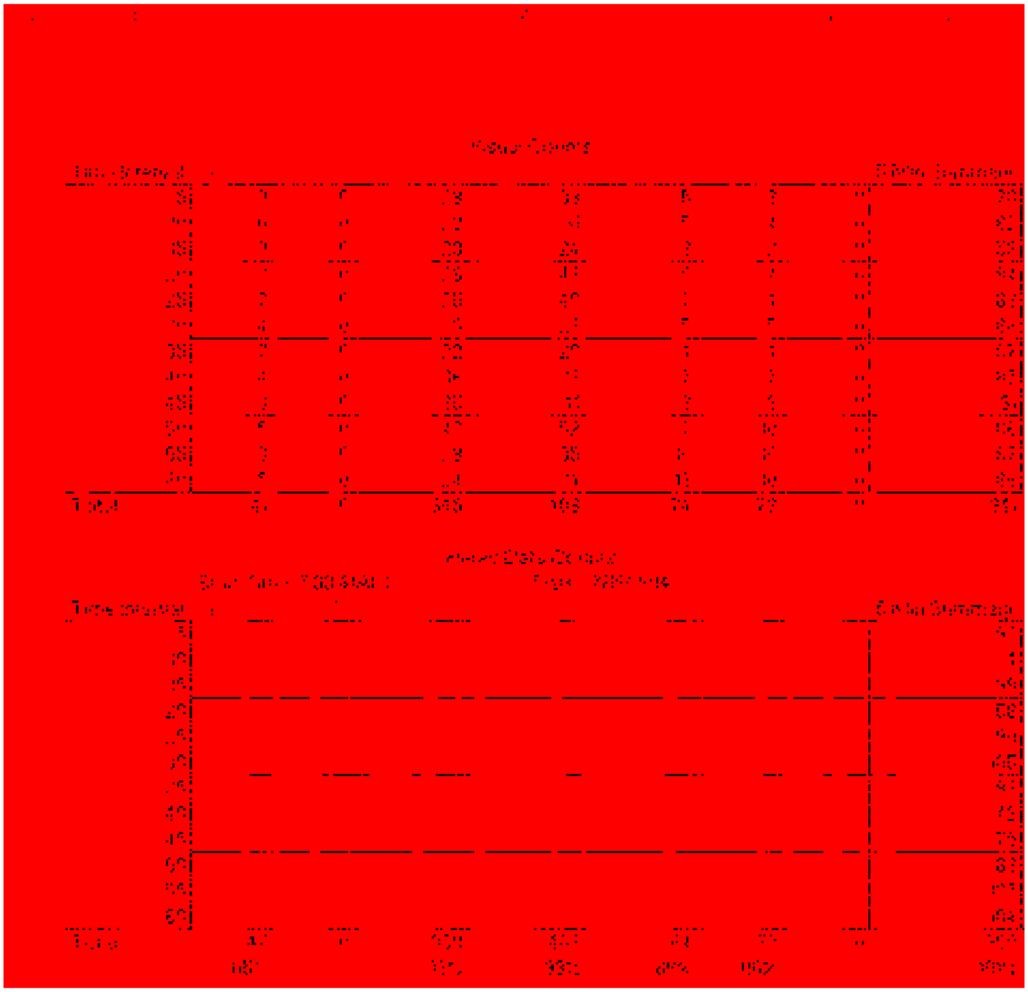
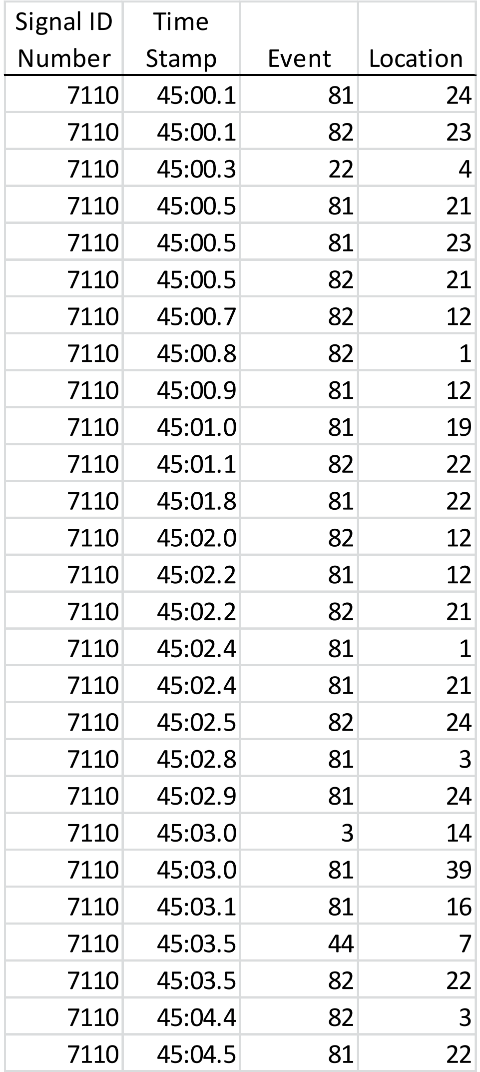


Figure 3-6: Manual and Hi-res Counts Spreadsheet



Signal ID Number	Time Stamp	Event	Location
7110	45:00.1	81	24
7110	45:00.1	82	23
7110	45:00.3	22	4
7110	45:00.5	81	21
7110	45:00.5	81	23
7110	45:00.5	82	21
7110	45:00.7	82	12
7110	45:00.8	82	1
7110	45:00.9	81	12
7110	45:01.0	81	19
7110	45:01.1	82	22
7110	45:01.8	81	22
7110	45:02.0	82	12
7110	45:02.2	81	12
7110	45:02.2	82	21
7110	45:02.4	81	1
7110	45:02.4	81	21
7110	45:02.5	82	24
7110	45:02.8	81	3
7110	45:02.9	81	24
7110	45:03.0	3	14
7110	45:03.0	81	39
7110	45:03.1	81	16
7110	45:03.5	44	7
7110	45:03.5	82	22
7110	45:04.4	82	3
7110	45:04.5	81	22

Figure 3-7: Hi-res Data from Traffic Controller

The first column in Figure 3-7 represents the signal identification (ID) number. Each intersection and controller has its own unique ID number. The second column is the time stamp. The time stamp provides the date and time of each event that passes through the controller. The third column of numbers represents an event that has occurred at this intersection. An example of an event is a traffic light turning green, and the accompanying code would be a 1. The final column of numbers represents the location (i.e., lane position) in the intersection that an event took place.

Further explanation on the last two columns will follow in the next paragraphs. It is important to know what the numbers mean and represent when reducing the Hi-res data.

When looking at the data, the last two columns may be confusing. The numbers and their respective meanings in the third column were determined by *Indiana Traffic Signal Hi Resolution Data Logger Enumeration,* a report published by the Joint Transportation Research Program (JTRP) (Sturdevant et al. 2012). As previously mentioned, this column represents events that occurred. The events of interest to the BYU research team were the "Phase Begin Green" event (see Table 3-2) and "Detector On" (see Table 3-3) event. There are many other events that occur at intersections. For further explanation on the other events, see the report published by the JTRP.

Table 3-2: Hi-res Data Logger Enumerations for Active Phase Events

Event Code	Event Descriptor	Parameter	Description
0	Phase On	Phase # (1-16)	Set when NEMA Phase On becomes active, either upon start of green or walk interval, whichever occurs first.
1	Phase Begin Green	Phase # (1-16)	Set when either solid or flashing green indication has begun. Do not set repeatedly during flashing operation.

Table 3-3: Hi-res Data Logger Enumerations for Detector Events

Event Code	Event Descriptor	Parameter	Description
81	Detector Off	DET Channel # (1-64)	Detector on and off events shall be triggered post any detector delay/extension processing.
82	Detector On	DET Channel # (1-64)	

The “Phase Begin Green” simply means that a traffic light turned green. Further description can be seen in Table 3-2 under the Description heading. The “Detector On” means that a sensor at this intersection was triggered on. Further description can be seen in Table 3-3 under the Description heading.

The fourth column of numbers in Figure 3-7 represents the locations that these events have taken place in the intersection. These numbers come from a numbering system that was created by UDOT. The location for this system of numbers is called the data pad, which is illustrated in Table 3-4. The data pad contains many of the intersections that are controlled and operated by UDOT. Within the data pad, there are various columns of data. Not all the columns were defined in the file, but the columns used in the study will be discussed below.

For the scope of this project, only two types of locations are looked at. The first number corresponds to the start of a green phase. This number can be seen in Table 3-4 as the third column from the left named “Phase.” The second type of location looked at is the sensor detection location. This can also be found in Table 3-4 in the seventh column from the left named “Location Code.” The numbers under these columns correspond to a specific direction and lane. The sixth column from the left, named “Direction,” describes the compass direction. For instance, “northbound” shows the north direction as well as which direction traffic is moving. The last column on the right corresponds to the specific lane in an intersection approach where “L” represents a left turn lane, “R” represents a right turn lane, and “T” represents a through lane. The number after the letter represents the lane position, starting nearest the median, if more than one lane exists for a movement. An example of the lane numbering method can be seen in Figure 3-8. With an interpretation of the Hi-res data and the data pad, data reduction can now take place.

Table 3-4: Data Pad for a Single Intersection

Signal ID		Phase			Direction	Location Code															Lane
7115		5			Northbound	23	0.0.0.0	0	0	0	0	2	0	0	0	0	36:44.7	0	1	1	L1
7115		5			Northbound	24	0.0.0.0	0	0	0	0	2	0	0	0	0	37:11.9	0	1	1	L2
7115		2			Northbound	25	0.0.0.0	0	0	0	0	2	0	0	0	0	37:50.7	0	1	1	T1
7115		2			Northbound	26	0.0.0.0	0	0	0	0	2	0	0	0	0	38:13.2	0	1	1	T2
7115		2			Northbound	27	0.0.0.0	0	0	0	0	2	0	0	0	0	38:48.2	0	1	1	T3
7115		2			Northbound	28	0.0.0.0	0	0	0	0	2	0	0	0	0	39:11.9	0	1	1	R1
7115		1			Southbound	35	0.0.0.0	0	0	0	0	2	0	0	0	0	27:28.5	0	1	1	L1
7115		1			Southbound	36	0.0.0.0	0	0	0	0	2	0	0	0	0	27:57.8	0	1	1	L2
7115		6			Southbound	37	0.0.0.0	0	0	0	0	2	0	0	0	0	29:08.3	0	1	1	T1
7115		6			Southbound	38	0.0.0.0	0	0	0	0	2	0	0	0	0	40:03.6	0	1	1	T2
7115		6			Southbound	39	0.0.0.0	0	0	0	0	2	0	0	0	0	40:18.6	0	1	1	T3
7115		6			Southbound	40	0.0.0.0	0	0	0	0	2	0	0	0	0	40:35.1	0	1	1	R1
7115		7			Eastbound	47	0.0.0.0	0	0	0	0	2	0	0	0	0	41:08.9	0	1	1	L1
7115		7			Eastbound	48	0.0.0.0	0	0	0	0	2	0	0	0	0	41:47.2	0	1	1	L2
7115		4			Eastbound	49	0.0.0.0	0	0	0	0	2	0	0	0	0	42:44.9	0	1	1	T1
7115		4			Eastbound	50	0.0.0.0	0	0	0	0	2	0	0	0	0	42:59.4	0	1	1	T2
7115		4			Eastbound	51	0.0.0.0	0	0	0	0	2	0	0	0	0	43:16.1	0	1	1	R1
7115		3			Westbound	59	0.0.0.0	0	0	0	0	2	0	0	0	0	44:08.0	0	1	1	L1
7115		3			Westbound	60	0.0.0.0	0	0	0	0	2	0	0	0	0	44:21.5	0	1	1	L2
7115		8			Westbound	61	0.0.0.0	0	0	0	0	2	0	0	0	0	44:41.8	0	1	1	T1
7115		8			Westbound	62	0.0.0.0	0	0	0	0	2	0	0	0	0	44:55.4	0	1	1	T2
7115		8			Westbound	63	0.0.0.0	0	0	0	0	2	0	0	0	0	00:00.0	0	1	1	R1

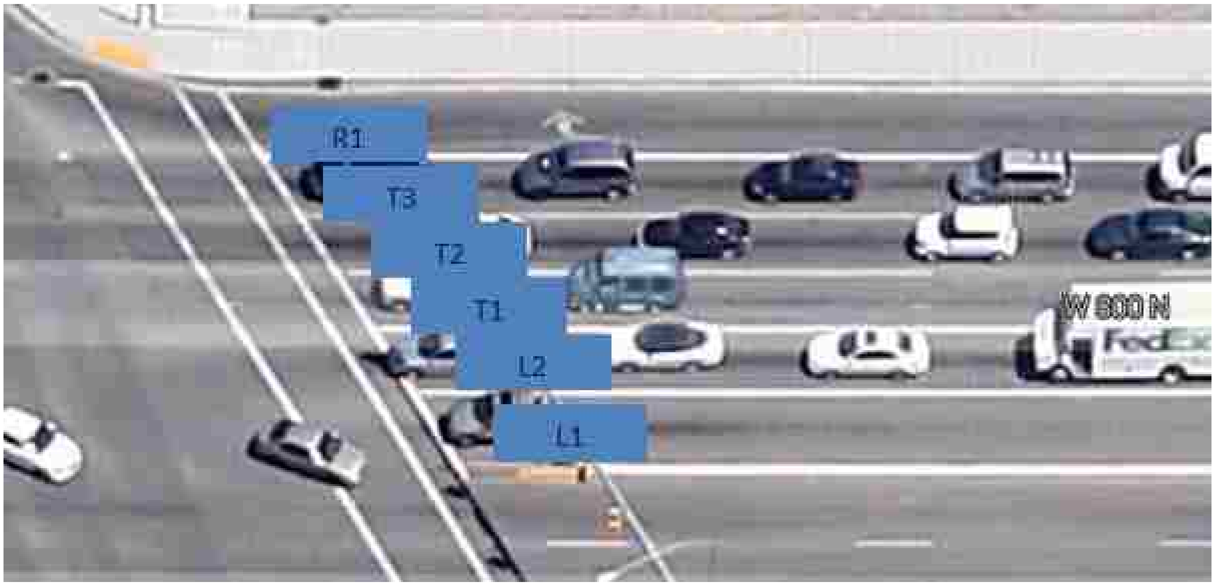
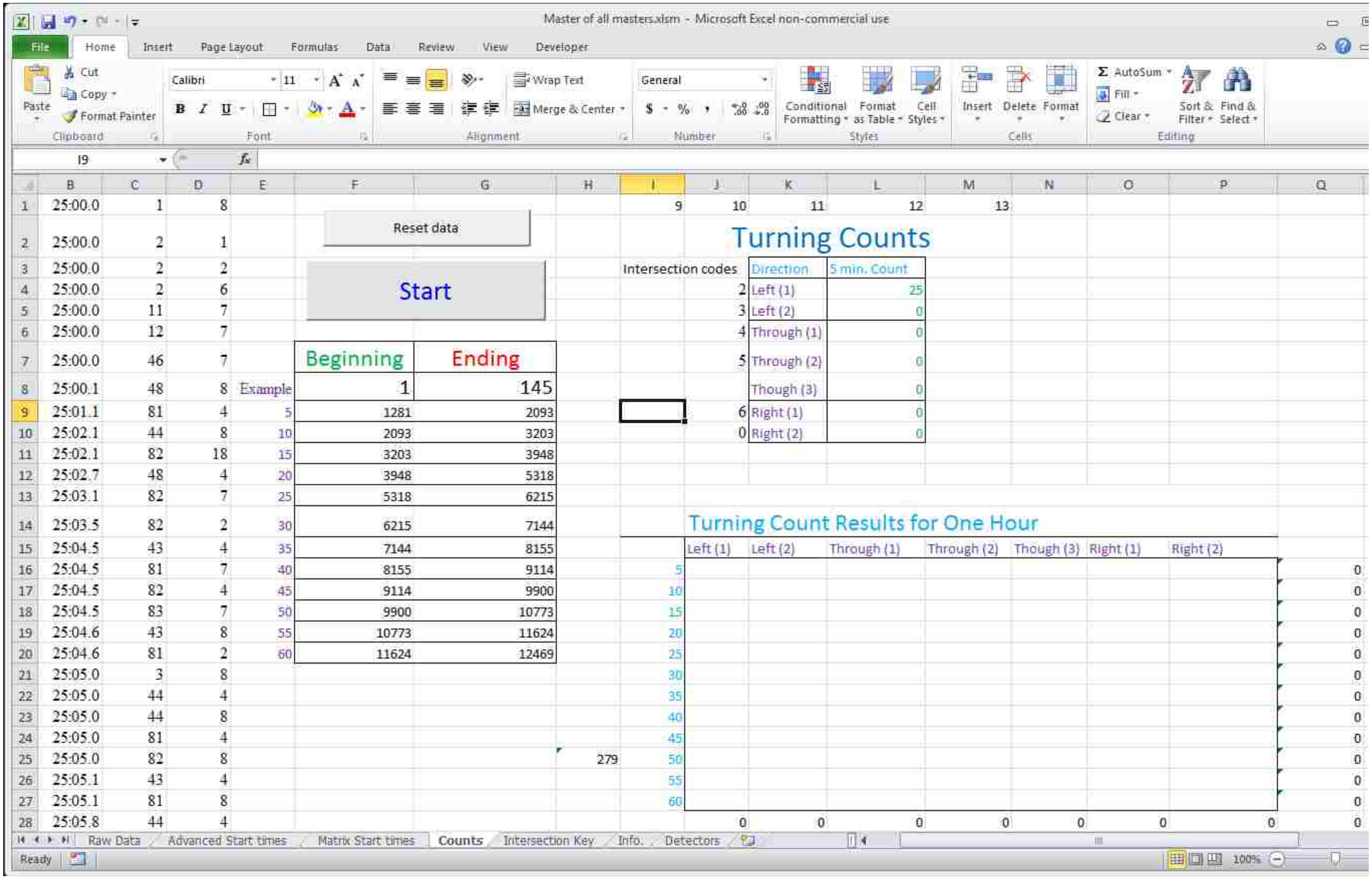


Figure 3-8: Lane Descriptions and Abbreviations

3.7.3 Data Reduction

Data reduction is the process that was performed to take the raw data from the traffic controller and reduce that data to a form that would be useful to the research team to conduct subsequent statistical analysis. To do this, the spreadsheet created by the BYU research team was first set up with the corresponding intersection information. Figure 3-9 provides an illustration of the spreadsheet created for this task. The first set of data that needs to be gathered is the data pad (Table 3-4). The data pad can be requested though UDOT. The data pad is a spreadsheet created by UDOT engineers for many of the intersections in Utah. It contains the sensor channels and phases for each lane in each movement of an intersection. The data pads can be found under the "Detectors" tab on the spreadsheet. This tab contains the data pads for many of the intersections in Utah. Using the signal ID number, the intersection of interest is located, copied, and pasted into the "Intersection Key" tab created in the spreadsheet by the research team for easier referencing.



	B	C	D	E	F	G	H
1	25:00.0	1	8				
2	25:00.0	2	1				
3	25:00.0	2	2				
4	25:00.0	2	6				
5	25:00.0	11	7				
6	25:00.0	12	7				
7	25:00.0	46	7		Beginning	Ending	
8	25:00.1	48	8	Example	1	145	
9	25:01.1	81	4	5	1281	2093	
10	25:02.1	44	8	10	2093	3203	
11	25:02.1	82	18	15	3203	3948	
12	25:02.7	48	4	20	3948	5318	
13	25:03.1	82	7	25	5318	6215	
14	25:03.5	82	2	30	6215	7144	
15	25:04.5	43	4	35	7144	8155	
16	25:04.5	81	7	40	8155	9114	
17	25:04.5	82	4	45	9114	9900	
18	25:04.5	83	7	50	9900	10773	
19	25:04.6	43	8	55	10773	11624	
20	25:04.6	81	2	60	11624	12469	
21	25:05.0	3	8				
22	25:05.0	44	4				
23	25:05.0	44	8				
24	25:05.0	81	4				
25	25:05.0	82	8				279
26	25:05.1	43	4				
27	25:05.1	81	8				
28	25:05.8	44	4				

I	J	K	L	M
9	10	11	12	13

Turning Counts

Intersection codes	Direction	5 min. Count
2	Left (1)	25
3	Left (2)	0
4	Through (1)	0
5	Through (2)	0
	Though (3)	0
6	Right (1)	0
0	Right (2)	0

Turning Count Results for One Hour

	Left (1)	Left (2)	Through (1)	Through (2)	Though (3)	Right (1)	Right (2)	
5								0
10								0
15								0
20								0
25								0
30								0
35								0
40								0
45								0
50								0
55								0
60								0
	0	0	0	0	0	0	0	0

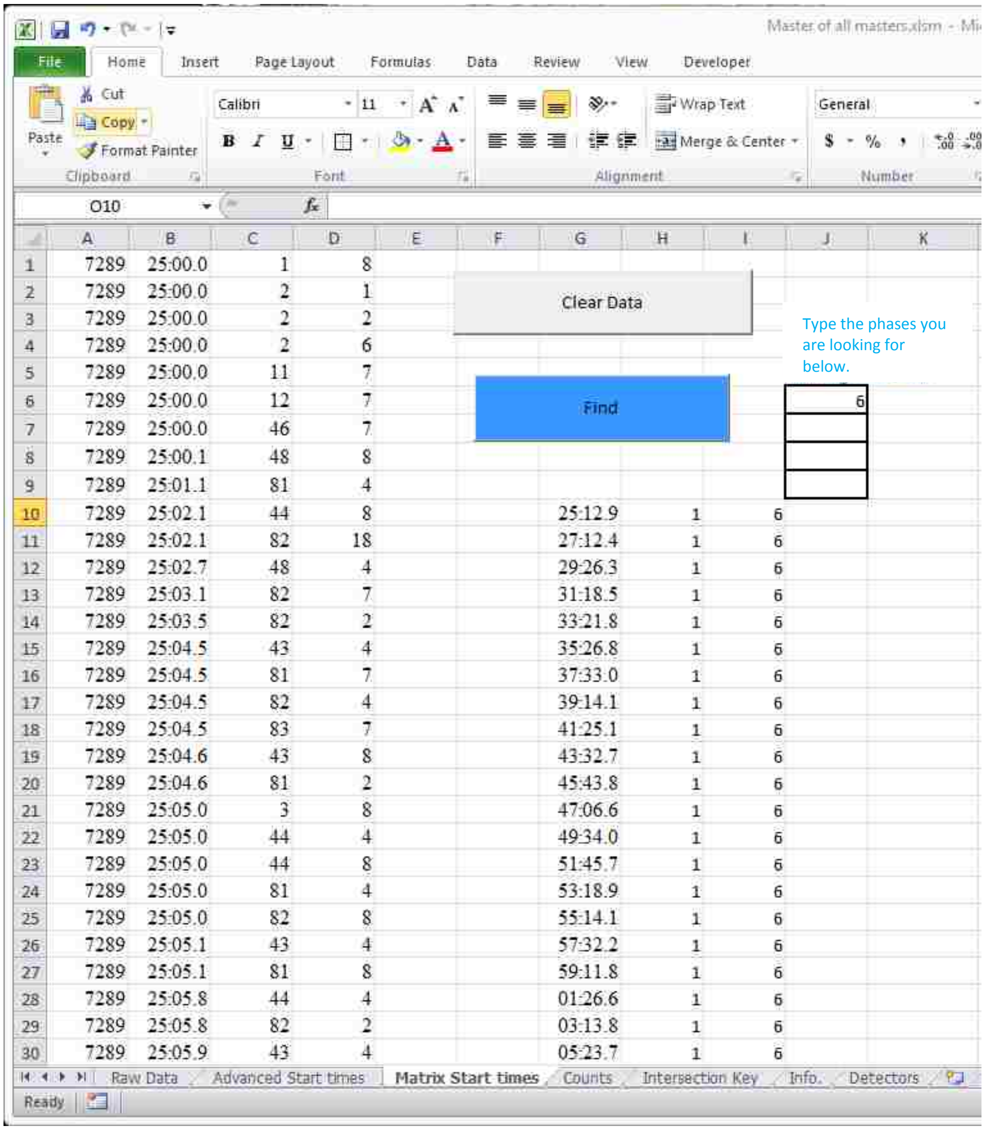
Figure 3-9: Counts Tab in the Data Reduction Spreadsheet

Once that is complete, the location code, found in the data pad, for each lane in the approach of interest needs to be found and copied into the "Counts" tab under the Intersection Code under Turning Counts (see Figure 3-9). When copying the location codes into the Counts tab, it is necessary to place them in the corresponding locations. If there is no lane that meets that requirement, the cell for that information is left blank, or 0 (zero) is entered.

The next item needed for data reduction also comes from the data pad, the phase number of the through movement that was counted. The visual or manual counts are always started when the through lane's green phase begins, unless otherwise noted on the count data. This number is located in the third column from the left in Table 3-4. Once this number is found, it needs to be typed into one of the four black outlined cells under "Type the phases you are looking for below," in the Matrix Start Times tab, as seen in Figure 3-10. This is the last piece of information that is needed from the data pad.

The last thing that needs to be imported into the spreadsheet is the Hi-res data that are provided by UDOT. This data set needs to be copied into two different places in the spreadsheet. The first is in the Matrix Start Times tab (see Figure 3-10), and the second is in the Counts tab (See Figure 3-9). When pasting the copied Hi-res data into the spreadsheets, it must be pasted in cell "A1" in both the Counts and Matrix Start Times tabs in the spreadsheet.

With the spreadsheet having been set up, the first thing that needs to take place is finding the common starting point in time for the manual counts and the Hi-res data. By using the Matrix Start Times tab (Figure 3-10) in the spreadsheet, the common start times can be found. The start times between the manual counts and the Hi-res data will not be the same since the clocks that are used may differ slightly.



Clear Data

Find

Type the phases you are looking for below.

	A	B	C	D	G	H	I	J
1	7289	25:00.0	1	8				
2	7289	25:00.0	2	1				
3	7289	25:00.0	2	2				
4	7289	25:00.0	2	6				
5	7289	25:00.0	11	7				
6	7289	25:00.0	12	7				6
7	7289	25:00.0	46	7				
8	7289	25:00.1	48	8				
9	7289	25:01.1	81	4				
10	7289	25:02.1	44	8	25:12.9	1	6	
11	7289	25:02.1	82	18	27:12.4	1	6	
12	7289	25:02.7	48	4	29:26.3	1	6	
13	7289	25:03.1	82	7	31:18.5	1	6	
14	7289	25:03.5	82	2	33:21.8	1	6	
15	7289	25:04.5	43	4	35:26.8	1	6	
16	7289	25:04.5	81	7	37:33.0	1	6	
17	7289	25:04.5	82	4	39:14.1	1	6	
18	7289	25:04.5	83	7	41:25.1	1	6	
19	7289	25:04.6	43	8	43:32.7	1	6	
20	7289	25:04.6	81	2	45:43.8	1	6	
21	7289	25:05.0	3	8	47:06.6	1	6	
22	7289	25:05.0	44	4	49:34.0	1	6	
23	7289	25:05.0	44	8	51:45.7	1	6	
24	7289	25:05.0	81	4	53:18.9	1	6	
25	7289	25:05.0	82	8	55:14.1	1	6	
26	7289	25:05.1	43	4	57:32.2	1	6	
27	7289	25:05.1	81	8	59:11.8	1	6	
28	7289	25:05.8	44	4	01:26.6	1	6	
29	7289	25:05.8	82	2	03:13.8	1	6	
30	7289	25:05.9	43	4	05:23.7	1	6	

Figure 3-10: Matrix Start Times Tab in the Data Reduction Spreadsheet

To use the Matrix Start Times spreadsheet, the phase number for the through movement that was counted needs to be entered into one for the four black boxes. Once this is done, pressing start will find the instances where the phase that was typed in turned green. The time stamp that corresponds to this event will be placed under the start button. Engineering judgment is needed to choose the correct time stamp that corresponds to the start time that the manual counts were completed.

Once the common start time has been determined in the Hi-res data, the row number that corresponds to it needs to be found, along with the row numbers of the corresponding 5-minute interval summary. With the row numbers found and copied into the appropriate location under the Start button, the macro in the Counts tab can be used. By pressing the Start button, the macro counts how many times the Detector On event, (i.e., 82), occurs in the location that was specified. The results will be placed in the Turning Counts Results for the One Hour table (Figure 3-9). These results can now be compared to the manual volume count results as seen in Figure 3-6.

3.8 Check for Accuracy

At the end of data reduction, the accuracy of the count was compared to the manual count that was performed. To ensure the validity of each count and to give the SmartSensor Matrix the benefit of the doubt, any study site with a traffic volume count that was below 85 percent of the ground-truth value was revisited and traffic volume counts redone to ensure that there were no potential problems with the traffic controller, BYU research team (i.e. error in traffic volume counts), UDOT traffic server, etc. If the redone traffic volume count turned out to be greater than 85 percent, then the original data would be removed and the more accurate data would be used for subsequent analysis. However, if the recount data turned out to be similar to the original results, the original results were kept and the results of the recounts were removed from the analysis.

3.9 Chapter Summary

There were many steps that were involved to complete data collection and to set up the designing of experiment for the project. The number of samples that were needed for each group was decided and the data collection process was established. The ground-truth data was considered to be the manual counts taken by the BYU research team. Each vehicle was to be counted as its rear axle passed the stop bar, and volume counts were to last the duration of an hour. Once manual counts were completed, the data from the SmartSensor Matrix, Hi-res data, were obtained from UDOT and reduced to determine the number of vehicles that the SmartSensor Matrix counted. Accuracy of traffic volume count data was defined as the percent of the traffic volume counts reported by the SmartSensor Matrix divided by the ground-truth traffic volume counts. To ensure accuracy of the data collection process, any traffic volume count that was below 85 percent accuracy was revisited and its traffic volume count was redone.

4 RESULTS OF STATISTICAL ANALYSIS

Following the conclusion of the data collection process, a series of statistical tests on the four factors, mentioned in Chapter 3, were performed. A Mixed Model ANOVA was used for this analysis. When these tests were run, a statistical block, which will be explained in the following section, was used to eliminate any interaction between the different intersections. The statistical analysis methodology and the statistical results are presented in this section.

4.1 Statistical Analysis Methodology

The analysis of the traffic volume count data obtained by the SmartSensor Matrix was performed by the Mixed Model ANOVA. To further understand the results from the Mixed Model ANOVA, a least squares mean comparison analysis was completed with a Tukey-Kramer p-value. This analysis helped the research team to find which factors used in this study significantly affected the accuracy of the traffic volume counts obtained by the SmartSensor Matrix at a 95 percent confidence level. To eliminate interaction between the different intersections, a statistical block was used. Further discussion on the Mixed Model ANOVA, statistical block, and Tukey Kramer p-value is presented in the following subsections.

4.1.1 Mixed Model Analysis of Variance (ANOVA)

An ANOVA is a test that compares the means of different groups to see if they are statistically equal or not. An ANOVA model is used when comparing more than two groups to find any significant statistical difference among the means of the different groups. A statistical analysis program called Statistical Analysis System (SAS) (SAS 2015) was used to perform the analysis.

The Mixed Model ANOVA analysis was performed based on the factors and data that were entered into the program. This analysis indicates whether or not a statistical difference in means is apparent in the data. A least squares mean comparison was also performed on any factors that were found to have statistical significance from the results of the Mixed Model ANOVA. A total of 14 different tests were performed that tested the significance of difference in the means for different factors and different combinations of factors.

4.1.2 Statistical Block

A statistical block is a tool that prevents interaction between groups of data. In this study, the groups were individual intersections. By using a block, the analysis only looks at the true variance between the means of the different groups. Thus, there is no added interaction between the different groups. This allows the true variation between different groups in an experiment and their respective means in each block to be found (Ramsey and Schafer 2002). This approach was taken to help the research team eliminate any extra interaction between the different factor combinations and their respective interactions.

4.1.3 Tukey-Kramer p-value

The Tukey-Kramer p-value was used to mitigate data snooping. The Tukey-Kramer is a numerical multiplier that is included in the analysis so the results from the statistical analysis can be used with a higher degree of confidence. The Tukey-Kramer p-value provides the best multiplier for comparisons to other groups as long as one group being tested is not a control group.

Data snooping can occur when the analyst uses the data to guide him/her towards a statistical test or result that is favorable to his/her needs or wants (Ramsey and Schafer 2002). The observation of data that occurred did influence some of the analyses that were completed.

4.2 Statistical Results

The results from the statistical analysis were helpful for understanding which factors in the study could be most responsible for affecting the accuracy of the SmartSensor Matrix. The factors that were analyzed were sensor position, traffic volume level, number of approach lanes, and posted speed limit. The first three factors were part of the original plan of the study while the last factor, posted speed limit, was added to the study after a few members of the TAC noted its possible effect on accuracy, especially at intersections with higher approach speeds.

In the course of analyzing the data, the BYU research team came across two 6-lane approaches that had accuracy values substantially lower, by 20 to 30 percent, than other intersections in the same 6-lane approach factor combination. These two approaches accounted for a total of six data points, that is, three different volume levels at each site. These intersections were re-evaluated by Wavetronix engineers to verify that the sensors had been correctly set up and working correctly before re-evaluation of the sensor could be completed. After the second data collection and reduction, the resulting accuracy remained relatively unchanged. Therefore, data points remained in the study since they were deemed valid. Because these data points remained in the study, it was decided that for each statistical test that was performed where the 6-lane approaches were included, the test would be performed twice: once with this particular 6-lane approach and the other without it. This approach was chosen because the lack of data points in the 6-lane approach group would be heavily influenced by the poorly performing data points for each site.

There were a total of 14 tests performed in this study. A list and descriptions of the 14 tests are found in Table 4-1. The first seven tests looked at the traffic volume count accuracy as an average of an approach. The second seven tests evaluated each approach lane of an intersection individually and thus resulted in another factor named lane-by-lane. These analyses were performed at the request of the TAC to determine whether or not the accuracy of the traffic volume counts changed by lane proximity to the SmartSensor Matrix, or, in other words, if the accuracy of the traffic volume counts changes the farther a lane is from the SmartSensor Matrix. In the least squares mean comparison table, there is the title of a factor followed by a number. The number represents the column for the factor.

The analysis results from the Mixed Model ANOVA and least squares mean comparison for these tests are presented in the following subsections.

Table 4-1: Fourteen Statistical Tests Performed

a) Total Approach Count Analysis

Test Number	Description of Tests
Test 1	All data, all factors included: sensor position number of lanes, volume level, and speed limit.
Test 2	Reduced model including number of lanes and volume level factors and using all data.
Test 3	Two 6-lane approaches removed, all factors – number of lanes, sensor position number, volume level, speed limit.
Test 4	Reduced model including number of lanes and volume level factors and two 6-lane approaches removed.
Test 5	5-lane approaches only, test to see if speed has effect, using the accuracy of the whole approach.
Test 6	6-lane approaches only, test to see if speed has effect, using the accuracy of the whole approach. All approaches are used.
Test 7	Same as above except some 6-lane approaches removed. 6-lane approaches only, test to see if speed has effect, using the accuracy of the whole approach.

Table 4-2: Fourteen Statistical Tests Performed (Continued)

b) Lane-by-Lane Count Analysis

Test Number	Description of Tests
Test 8	3-lane approaches only, all position, all data: sensor position, volume level, speed limit, and lane-by-lane.
Test 9	4-lane approaches only, sensor position, volume level, speed limit, and lane-by-lane.
Test 10	5-lane approaches only, volume level, speed limit, lane-by-lane, sensor position 1 only.
Test 11	6-lane approaches only, volume level, speed limit, lane-by-lane, sensor position 1 only, all data.
Test 12	6-lane approaches only, volume level, speed limit, lane-by-lane, sensor position 1 only, poorly performing approaches removed.
Test 13	All data from Sensor Position 1, all factors included: volume level, speed limit, and lane-by-lane.
Test 14	All data from Sensor Position 1, all factors included: volume level, speed limit, and lane-by-lane, two 6-lane approaches removed.

4.2.1 Test 1

Test 1 was performed to determine which factors were significant in the accuracy of the volume count data collected by the SmartSensor Matrix. This test used all four factors and all the data that were collected. The accuracy data, expressed in percentage, were data values of the average of the accuracy of all approach lanes. This test yielded the results shown in Table 4-3. As shown in Table 4-3, there is only one factor that is statistically significant, that is, number of lanes. However, there is another factor, volume level, which is nearly statistically significant. A factor is considered significant when its p-value is less than or equal to 0.05. Because of these findings, Test 2 was performed, and included only the number of lanes and volume level factors.

Table 4-3: Results from Test 1

Factors	p-value
Number of Lanes	< 0.0001
Sensor Position Number	0.0946
Volume Levels	0.0515
Speed Limit	0.4003

4.2.2 Test 2

Test 2 was performed on a reduced model of Test 1 and excluded the two least significant factors, which were sensor position and posted speed limit. The results from this test are found in Table 4-4. As seen in Table 4-4, number of lanes remains a significant factor while volume level becomes less conclusive. To further investigate the significance of these factors, Tukey-Kramer p-values from the least squares mean comparisons were examined. Only the factors found to be significant in the test were further analyzed. Table 4-4 presents the results of this analysis.

Table 4-4: Results from Test 2

Factors	p-value
Number of Lanes	< 0.0001
Volume Level	0.0934

The least squares mean comparisons of number of approach lanes indicated that several comparisons contain results that are determined to be significant. They are 2- and 6- and 3- and 6-lane approaches, as shown in Table 4-5a. A pattern emerges with 6-lane approaches being statistically different than all the other number of approach lanes. When examining the least squares mean that corresponds to each number of lanes, it is seen that the larger the intersection, hence the more number of lanes, the lower the accuracy of volume counts. However, there is a large jump in the least squares mean between 5- and 6-lane approaches as shown in Table 4-5b. The large difference in the least squares mean may be the cause of comparisons involving 6-lane approaches to become significant. The standard error of the least squares means and the confidence intervals (CI) are also presented in Table 4-5.

Table 4-5: Numbers of Lanes Least Squares Mean Comparison

a) Tukey-Kramer p-value

Number of Lanes (a)	Number of Lanes (b)	Tukey-Kramer p-value
2	3	0.9457
2	4	0.4335
2	5	0.3213
2	6	0.0155
3	4	0.7019
3	5	0.4852
3	6	0.0187
4	5	0.0984
4	6	0.1559
5	6	0.3499

b) Mean, Standard Error, CI Values

Number of Lanes	Mean (%)	Standard Error (%)	CI (%) Lower	CI (%) Upper
2	100.1	2.04	96.0	104.2
3	98.1	1.56	95.0	101.3
4	95.2	1.91	91.3	99.0
5	93.7	2.44	88.8	98.6
6	87.2	3.14	80.9	93.6

4.2.3 Test 3

Test 3 is the same as Test 1 with the exception of the data included in the analysis. As previously mentioned, there were two 6-lane approach intersections that consistently performed poorly, while the other intersections in the same group performed substantially better. For this reason, it was decided that all tests that included the intersections that performed poorly would be done once with (Test 1) and once without the two intersections in question (Test 3). This test included all four factors and all data other than the poorly performing approaches. The results from this test are presented in Table 4-6. From this test, excluding the poorly performing approaches, it was found that the number of lanes is the only significant factor with a p-value of 0.0007.

Table 4-6: Results from Test 3

Factors	p-value
Number of Lanes	0.0007
Sensor Position Number	0.0772
Volume Level	0.0897
Speed Limit	0.4715

4.2.4 Test 4

The fourth test is the reduced model of Test 3, which only includes the two most significant factors, number of lanes and sensor position number. All data except for the poorly performing approaches were used in this test. The results from this test are found in Table 4-7. From Table 4-7, it can be seen that the number of lanes is still the only significant factor with a p-value of less than 0.0001.

Table 4-7: Results from Test 4

Factor	p-value
Number of lanes	< 0.0001
Sensor Position Number	0.1237

To further investigate the findings of Test 4, the least squares mean comparison was performed to see which comparisons were significant when poorly performing approaches were removed from the data. The results from this test are found in Table 4-8a. These results are similar to the results of the least squares mean comparison performed in Test 2. In this comparison, there are only two comparisons that were found to be significant, 2- and 6- and 3- and 6-lane approach comparisons. It was believed that larger intersections would experience a difference in accuracy as an intersection became larger. However, it was not expected that there would be a significant difference between 5-lane and 6-lane approaches when there was only a one lane difference between the two when looking at the means.

To further investigate the reasoning for these results, the least squares means for each number of approach lanes are examined, and the results are shown in Table 4-8b. Once again, a trend was found in the means. The larger an intersection, that is, the larger the number of lanes, the less accurate the volume counts will be. Once again, the largest jump occurred between the 5- and 6-lane approaches. Because the smaller intersections had larger mean accuracy values and the larger intersections had lower mean values, this is most likely the cause of the significant difference in the 2- and 6- and 3- and 6-lane approach comparisons. The 6-lane approaches have the largest standard error of all the approaches, indicating a larger distribution in accuracy in the values.

Table 4-8: Numbers of Lanes Least Squares Mean Comparison

a) Tukey-Kramer p-value

Number of Lanes (a)	Number of Lanes (b)	Tukey-Kramer p-value
2	3	0.9457
2	4	0.4335
2	5	0.3213
2	6	0.0155
3	4	0.7019
3	5	0.4852
3	6	0.0187
4	5	0.0984
4	6	0.1559
5	6	0.3499

Table 4-8: Numbers of Lanes Least Squares Mean Comparison (Continued)

b) Mean, Standard Error, CI Values

Number of Lanes	Mean (%)	Standard Error (%)	CI (%)	
			Lower	Upper
2	100.1	2.04	95.9	104.2
3	98.1	1.56	95	101.3
4	95.2	1.91	91.3	99
5	93.7	2.44	88.8	98.6
6	87.2	3.14	80.9	93.6

4.2.5 Test 5

Test 5 was performed to test which factors had an effect on the accuracy when only 5-lane approaches were analyzed. This test included all data for 5-lane approaches and examined only two factors, volume level and speed limit. Sensor position and number of lanes factors were eliminated by default since only 5-lane approaches were examined and only sensor position one has this level of approach lanes. The results from this test can be found in Table 4-9. From this test, it can be seen that the speed limit factor became significant when only 5-lane approaches were analyzed.

Table 4-9: Results from Test 5

Factor	p-value
Volume Level	0.1604
Speed Limit	0.0070

To further investigate the findings of Test 4, the least squares mean comparison was performed to see which comparisons were statistically significant. The results from this test are given in Table 4-10a. The comparisons that were found to be significant were 30 mph and 35 mph speed limits and 35 mph and 45 mph speed limits. Looking at the least squares means in Table 4-10b, it can be seen that the least squares mean for the 35 mph speed limit approach is the lowest in this test. The highest least squares mean occurred at 30 mph speed limit approaches. It makes sense that the largest and smallest means would result in a significant difference in means. However, the least squares mean for the 45 mph approach is not the second highest but rather the third highest. Because the sample sizes are smaller and there is more variability in the data sets, as indicated by the standard error, the third highest least squares mean became significant when compared to the lowest least squares mean.

Table 4-10: Speed Limit Least Squares Mean Comparison

a) Tukey-Kramer p-value

Speed Limit (a)	**Speed Limit (b)**	**Tukey-Kramer p-value**
25	30	0.7972
25	35	0.9900
25	40	0.9733
25	45	0.9498
25	50	0.9598
30	35	0.0154
30	40	0.9950
30	45	0.9769
30	50	0.9884
35	40	0.2832
35	45	0.0223
35	50	0.0846
40	45	1.0000
40	50	1.0000
45	50	1.0000

Table 4-11: Speed Limit Least Squares Mean Comparison (Continued)

b) Mean, Standard Error, CI Values

Speed Limit	Mean (%)	Standard Error (%)	Lower	Upper
25	90.0	6.13	76.8	103.3
30	99.5	3.02	93.1	106.0
35	85.6	1.63	82.1	89.1
40	96.3	4.30	87.1	105.6
45	96.4	2.34	91.4	101.5
50	96.5	3.06	90.0	103.0

4.2.6 Test 6

Test 6 is similar to that of Test 5, except that only 6-lane approaches were analyzed. This test included all 6-lane approaches and two factors, volume level and speed limit. The results from this analysis are found in Table 4-12. As can be seen in Table 4-12, there were no significant factors when this test was performed. Both factors resulted in p-values larger than 0.05, indicating that for only 6-lane approaches neither of these factors statistically influences the accuracy of volume counts by the SmartSensor Matrix.

Table 4-12: Results from Test 6

Factors	p-value
Volume Levels	0.3029
Speed Limit	0.0971

4.2.7 Test 7

Test 7 is the same test as the one performed in Test 6, except that two 6-lane approaches were removed because of their poor performance. Two factors, volume levels and speed limit, were again tested. The results from this test are found in Table 4-13. As seen in Table 4-13, the outcome remained unchanged; neither of these two factors was significant, indicating that the accuracy of the volume counts is not affected by volume level or by speed limit.

Table 4-13: Results from Test 7

Factors	p-value
Volume Levels	0.1183
Speed Limit	0.0803

4.2.8 Test 8

In Test 8, the lane-by-lane volume count accuracy is tested. The goal behind this test is to see if there is a difference in accuracy as the approach lanes get farther from the location of the SmartSensor Matrix traffic sensor. In this test, only 3-lane approaches were tested with four factors, sensor position, speed limit, lane-by-lane, and volume level because only 3-lane approaches had enough data for a rigorous statistical analysis for these factor combinations. Each sensor position was looked at separately because, depending on the sensor position, the lanes that are closest to the sensors change, as illustrated previously in Figure 2-3. The results from this analysis are found in Table 4-14. As shown in Table 4-14, there were no significant factors that affected the accuracy of lane-by-lane counts at 3-lane approaches.

Table 4-14: Results from Test 8

Factors	p-value
Lane-by-Lane	0.8593
Speed Limit	0.1381
Sensor Position Number	0.4515
Volume Level	0.6444
Lane and Position Interaction	0.9822

4.2.9 Test 9

Test 9 is similar to Test 8 with the only difference being the number of approach lanes. In this test, only 4-lane approaches were analyzed with four factors, lane-by-lane, volume level, speed limit, and an interaction between the sensor position and the lane location. Once again, sensor positions are looked at separately because the lanes that are closest to the sensors change depending on the sensor position, as illustrated previously in Figure 2-3. The results of this test are found in Table 4-15. From this test, it can be seen that there were two factors that were significant: speed limit and lane location and position interaction.

Table 4-15: Results from Test 9

Factors	p-value
Lane-by-Lane	0.2258
Volume Level	0.8259
Speed Limit	0.0295
Lane Location and Position Interaction	0.0023

To further investigate the effect of the factors that were found to be significant, a least squares mean comparison was performed using the Tukey-Kramer p-value. The effect of speed limit was first analyzed. It was found that only one comparison in this analysis was significant, 35 mph and 45 mph, as illustrated in Table 4-16a. Looking at the least squares means values in Table 4-16b, it can be seen that 35 mph had the largest mean and 45 mph had the second lowest mean. The difference in least squares means between these two speed limits supports this statistical finding. The 45 mph speed limit is not the lowest mean, and a possible reason that the lowest mean and the highest mean did not have a significant difference is that the approach group had a large standard error of the means compared to that of the 45 mph approaches.

Table 4-16: Speed Limit Least Squares Mean Comparison

a) Tukey-Kramer p-value

Speed Limit (a)	Speed Limit (b)	Tukey-Kramer p-value
25	30	0.7986
25	35	0.1871
25	40	0.6362
25	45	0.9989
30	35	0.7595
30	40	0.9958
30	45	0.7348
35	40	0.9680
35	45	0.0327
40	45	0.5775

b) Mean, Standard Error, CI Values

Speed Limit	Mean (%)	Standard Error (%)	CI (%)	
			Lower	Upper
25	88.8	6.91	75.0	102.9
30	97.4	4.73	88.0	106.9
35	103.5	2.77	98.0	109.0
40	100	5.63	88.8	111.2
45	90.6	3.95	82.4	98.5

The second factor to have a significant effect on the accuracy of the lane-by-lane counts was the interaction of lane number and sensor position. By this factor being significant, it shows that certain lanes are more accurate than others for a particular sensor position number. The least squares mean of lane number and sensor position combinations are found in Table 4-17a. As shown in Table 4-17a, only comparisons between the same sensor positions were conducted.

Of the significant comparisons found, only one was of interest to the study. Looking at the least squares mean in Table 4-17b, under the sensor position 3, lane 3 had the highest least squares mean with a 127.7 percent, and lane 1 had the lowest least squares mean of 90.8 percent for position 1. Between these two lanes was a difference of over 37 percent in accuracy. This large difference between the two lanes caused it to become significant.

Table 4-17: Lane and Sensor Position Least Squares Mean Comparison

a) Tukey-Kramer p-value

Lane (a)	Sensor Position (a)	Lane (b)	Sensor Position (b)	Tukey-Kramer p-value
1	3	3	3	0.0175

b) Mean, Standard Error, CI Values

Lane	Sensor Position	Mean (%)	Standard Error (%)	CI (%)	
				Lower	Upper
1	1	96.7	3.51	89.7	103.7
1	2	80.8	10.46	60.1	101.7
1	3	90.8	7.51	75.8	105.7
2	1	95.5	3.51	88.5	102.4
2	2	103.6	10.46	82.8	124.4
2	3	95.6	7.51	80.7	97.0
3	1	90.0	3.51	83.0	124.4
3	2	86.8	10.46	66.0	110.6
3	3	127.7	8.07	111.6	97.0
4	1	99.8	3.51	92.8	106.8
4	2	85.8	10.46	65.0	106.6
4	3	99.6	7.51	84.7	114.6

4.2.10 Test 10

Test 10 is similar to Test 9 with the only difference being the number of approach lanes. In this test, only 5-lane approaches were analyzed, with the speed and volume levels as the factors. There were no other sensor positions other than position 1 that had 5-lane approaches. The results of this test are found in Table 4-18. From this test, only the speed limit was found to be a significant factor affecting the accuracy of the volume counts.

Table 4-18: Results from Test 10

Factor	p-value
Lane-by-Lane	0.0659
Volume Level	0.2093
Speed Limit	< 0.0001

To further investigate the factors that were found to be significant, a least squares mean comparison was performed and Tukey-Kramer p-values were computed. Speed limit is the only factor analyzed by this test because it was the only significant factor. The comparison between different speed limits are found in Table 4-19a. There are three comparisons that were found to be significant, 30 mph and 35 mph, 35 mph and 45 mph, and 35 mph and 50 mph. One speed limit that each of these comparisons has in common is 35 mph.

When examining the least squares mean for speed limits in Table 4-19b, the first thing that is apparent is that the 35 mph group has a mean of 87.7, which is about 10 percent lower than the rest of the least squares means. The rest of the least squares means are clustered around 97. The only speed limit that was not found to be significant when compared to the 35 mph was 40 mph. The p-value that was calculated for this comparison was 0.068 and close to the pre-determined alpha value of 0.05; hence, the mean for the 40 mph approach had the second highest mean, but their difference was not significant. This might be due to the high standard error of the mean of 3.4, as shown in Table 4-19b; the standard errors of mean for other speed limit groups are much lower than that of 40 mph approaches. Based on the data that were collected for this study, it can be said that a 35 mph speed limit has the largest negative effect on these sensors that have 5-lane approaches.

Table 4-19: Speed Limit Least Squares Mean Comparison

a) Tukey-Kramer p-value

Speed Limit (a)	Speed Limit (b)	Tukey-Kramer p-value
30	35	0.0021
30	40	0.9996
30	45	0.9849
30	50	0.9968
35	40	0.068
35	45	0.0015
35	50	0.0098
40	45	0.9998
40	50	1.0000
45	50	0.9999

b) Mean, Standard Error, CI Values

Speed Limit	Mean (%)	Standard Error (%)	CI (%)	
			Lower	Upper
30	98.4	2.41	93.6	103.2
35	87.7	1.41	84.9	90.5
40	97.5	3.44	90.7	104.4
45	96.8	1.88	93.1	100.6
50	97.2	2.42	92.4	102.0

4.2.11 Test 11

Test 11 is similar to Test 10 with the only difference being the number of approach lanes. In this test, only 6-lane approaches were analyzed, with the speed and volume levels as the factors, and all data collected were used. There were no other sensor positions other than position 1 that had 5-lane approaches. The results of this test are found in Table 4-20. As seen in the table, all factors were found to be statistically significant factors that affected the accuracy of the sensor.

Table 4-20: Results from Test 11

Factor	p-value
Lane by Lane	0.0477
Volume Level	0.0043
Speed Limit	0.0058

To further investigate the factors that were found to be significant, a least squares mean comparison test was performed using the Tukey-Kramer p-value. Table 4-21b shows the results of this comparison. First, effects of speed limit were evaluated. As seen in Table 4-21a, two comparisons were found to be significant, the 35 mph and 40 mph and the 35 mph and 45 mph comparisons. Once again, 35 mph is common in both combinations. The least squares mean value is about 10 percent higher than the values of the other two speed limits, which have similar least squares means (86.4 and 84.8).

Table 4-21: Speed Limit Least Squares Mean Comparison

a) Tukey-Kramer p-value

Speed Limit (a)	Speed Limit (b)	Tukey-Kramer p-value
35	40	0.0066
35	45	0.0223
40	45	0.9001

b) Mean, Standard Error, CI Values

			CI (%)	
Speed Limit	Mean (%)	Standard Error (%)	Lower	Upper
35	94.7	2.74	89.2	100.2
40	83.4	2.27	78.8	87.9
45	84.8	2.36	80.1	89.5

The second factor that was significant was volume level. The comparisons between the three volume levels can be seen in Table 4-22a. From Table 4-22a, there are two comparisons found to be significant: high and mid and high and low volume levels. Both comparisons have high volumes in common. When looking at the least squares means for the volume levels in Table 4-22b, it can be seen that the high volume level has the lowest mean accuracy value. The other two means are similar in value.

Table 4-22: Volume Level Least Squares Mean Comparison

a) Tukey-Kramer p-value

Volume Level (a)	Volume Level (b)	Tukey-Kramer p-value
High	Mid	0.0054
High	Low	0.0348
Low	Mid	0.7028

b) Mean, Standard Error, CI Values

Volume Level	Mean (%)	Standard Error (%)	CI (%) Lower	CI (%) Upper
High	81.0	2.33	76.3	85.7
Mid	89.5	2.42	84.7	94.4
Low	92.4	2.61	87.1	97.6

The third factor that was significant was lane-by-lane. Based on the comparison results in Table 4-23a, there were two comparisons that were significant, lanes 1 and 2 and lanes 2 and 4. Upon examining the mean values in Table 4-23b, it can be seen that lane 2 had the highest least squares mean of all the lanes and lane 4 had the lowest. Lane 4 had the third lowest mean with a difference of around 15 percent. The second lowest least squares mean was not significant. This might have resulted because the standard error of the means of all lanes was 3.4. Other than lane 2, the rest of the lanes' least squares means are all clustered around 85.

The standard error for this factor is all the same because the sample sizes for these lanes are all the same. This is because all lanes in the data have the same number of samples since only 6-lane approaches were included in this test. The standard error is calculated by taking the pooled standard deviation and dividing it by the squares root of the sample size; thus, if the sample size is the same, then the standard error is also the same.

Table 4-23: Lane-by-Lane Least Squares Mean Comparison

a) Tukey-Kramer p-value

Lane (a)	Lane (b)	Tukey-Kramer p-value
1	2	0.1517
1	3	0.9996
1	4	0.9953
1	5	1.0000
1	6	0.9997
2	3	0.0743
2	4	0.0460
2	5	0.1154
2	6	0.2651
3	4	1.0000
3	5	1.0000
3	6	0.9897
4	5	0.9988
4	6	0.9649
5	6	0.9983

b) Mean, Standard Error, CI Values

			CI (%)	
Lane	**Mean (%)**	**Standard Error (%)**	**Lower**	**Upper**
1	86.2	3.44	79.3	93.1
2	98.1	3.44	91.2	105.0
3	84.6	3.44	77.7	91.5
4	83.7	3.44	76.8	90.6
5	85.5	3.44	78.7	92.4
6	87.6	3.44	80.7	94.5

4.2.12 Test 12

Test 12 is similar to Test 11 with the exception of the data used in the test. In this test, only 6-lane approaches were analyzed with three factors: speed limit, volume level, and Lane-by-Lane.

All the 6-lane approaches were used with the exception of one 6-lane approach that had unusually low accuracy values. The results of the analysis are found in Table 4-24. From the table, it can be seen that all the factors were significant, as seen below.

Table 4-24: Results from Test 12

Factors	p-value
Speed Limit	0.0155
Volume Level	0.0067
Lane-by-Lane	0.0217

To further investigate the factors that were found to be significant, a least squares mean comparison was performed on speed limit using Tukey-Kramer p-value. The results of this test are found in Table 4-25a. As seen in the table, there is one comparison that is significant, 35 mph and 40 mph speed limit comparison. When examining the least squares means in Table 4-25b, the highest and lowest least squares means correspond to 35 mph and 40 mph speed limits.

Table 4-25: Speed Limit Least Squares Mean Comparison

Speed Limit (a)	Speed Limit (b)	Tukey-Kramer p-value
35	40	0.0118
35	45	0.3800
40	45	0.4857

b) Mean, Standard Error, CI Values

			CI (%)	
Speed Limit	Mean (%)	Standard Error (%)	Lower	Upper
35	94.7	2.71	89.2	100.2
40	82.4	3.01	76.3	88.5
45	88.3	3.91	80.4	96.2

The second factor that was significant was volume level. The comparisons between the three volume levels are found in Table 4-26a. Among the comparisons, only one was found to be significant: high and low volume levels. When looking at the least squares mean for the volume levels in Table 4-26b, it can be seen that the high volume level has the lowest least squares mean value and the low volume level has the highest least squares mean of accuracy. The difference between these least squares means is greater than 15 percent.

Table 4-26: Volume Level Least Squares Mean Comparison

a) Tukey-Kramer p-value

Volume Level (a)	**Volume Level (b)**	**Tukey-Kramer p-value**
High	Low	0.0047
High	Mid	0.1673
Low	Mid	0.2274

b) Mean, Standard Error, CI Values

Volume Level	**Mean (%)**	**Standard Error (%)**	**CI (%)**	
			Lower	**Upper**
High	80.4	3.51	73.3	87.5
Mid	89.0	2.89	89.8	94.8
Low	96.1	3.10	83.1	102.3

The third factor that was significant was lane-by-lane. According to the analysis results shown in Table 4-27a, there were two comparisons that were significant, lanes 1 and 2 and lanes 2 and 5 comparisons. Upon examining the least squares mean in Table 4-27b, it can be seen that lane 2 had the highest mean value of all the lanes and lane 5 had the lowest. Lane 1 had the second lowest mean value with a difference of around 20 percent compared to lane 5. Other than lane 2, least squares means of the rest of the lanes range from 89 down to 82.

The standard error for this factor is all the same because the sample sizes for these lanes are all the same. This is because all lanes in the data have the same number of samples since only 6-lane approaches were included in this test. The standard error is calculated by taking the pooled standard deviation and dividing it by the square root of the sample size; thus, if the sample size is the same, then the standard error is the same.

Table 4-27: Lane-by-Lane Least Squares Mean Comparison

a) Tukey-Kramer p-value

Lane (a)	Lane (b)	Tukey-Kramer p-value
1	2	0.0400
1	3	0.9997
1	4	0.9999
1	5	0.9999
1	6	0.9545
2	3	0.0793
2	4	0.0655
2	5	0.0216
2	6	0.2455
3	4	1.0000
3	5	0.9941
3	6	0.9928
4	5	0.9974
4	6	0.9864
5	6	0.8773

b) Mean, Standard Error, CI Values

Lane	Mean (%)	Standard Error (%)	CI (%)	
			Lower	Upper
1	84.2	4.32	75.5	93.0
2	102.9	4.32	94.2	111.7
3	86.0	4.32	77.3	94.7
4	85.5	4.32	76.7	94.2
5	82.7	4.32	74.0	91.5
6	89.4	4.32	80.7	98.2

4.2.13 Test 13

Test 13 is similar to that of Test 12 where only three factors are examined: lane-by-lane, volume level, and speed limit. This test uses all the data that were collected for sensor position 1 only. However, the main focus of this test was to see if there is a significant difference the farther an approach lane is away from the sensor as a whole. The results of Test 13 can be found in Table 4-28.

Table 4-28: Results from Test 13

Factor	p-value
Lane-by-Lane	0.0524
Volume Level	0.0035
Speed Limit	0.0044

On previous tests where all data were used, such as Tests 1 and 3, a full and reduced model was performed. However, in this case, no factor was insignificant enough to remove from the model to create a reduced model. The lane-by-lane factor did not meet the defined 0.05 p-value cut off, 0.0524, but was very close to it and thus remained in the model.

As seen in Table 4-28, there are two factors that had p-values less than 0.05, volume level and speed limit. The lane-by-lane factor had a p-value of 0.0524 and thus did not meet the minimum p-value cut off. To further examine the significant factors, a least squares mean comparison was performed for each of the significant factors. The lane-by-lane factor is also included since the main purpose of this test was to see if there was a difference in counting accuracy the farther an approach lane is from the sensor.

The first factor examined was lane-by-lane. The results of the least squares mean comparison can be found in Table 4-29a. From this table, it can be seen that there are no lane comparisons that are significant. There is one comparison that is close to the 0.05 cut off value, lanes 2 and 3 with a p-value of 0.0721. This comparison is close to being a significant factor but is not significant. The remaining comparisons had much higher p-values. The mean values that correspond to lane 2 and lane 3 are the highest and the third lowest least squares means, respectively. The reason that the third lowest value was significant is most likely due to the sample size that corresponds to lane 3. Every sample included in this test has a minimum of 3 lanes because the smallest size intersection included in the study has 3 lanes. The standard error is also smaller for the number of approach lanes of 3 or less.

Table 4-29: Lane by Lane Least Squares Mean Comparison

Lane (a)	Lane (b)	Tukey-Kramer p-value
1	2	0.4652
1	3	0.9369
1	4	0.9983
1	5	0.9509
1	6	0.8829
2	3	0.0721
2	4	0.2521
2	5	0.1414
2	6	0.2221
3	4	0.9965
3	5	1.0000
3	6	0.9962
4	5	0.9963
4	6	0.9649
5	6	0.9981

b) Mean, Standard Error, CI Values

Lane	Mean (%)	Standard Error (%)	CI (%) Lower	CI (%) Upper
1	93.8	1.95	89.9	97.6
2	98.4	1.95	94.5	102.2
3	91.4	1.95	87.6	95.3
4	92.7	2.05	88.7	96.7
5	91.2	2.41	86.5	96.0
6	89.4	3.69	82.1	96.7

The standard error for lanes 1, 2, and 3 are all the same because the sample sizes for these lanes are all the same. This is because all the intersections included in the study had at least 3 approach lanes. The standard error is calculated by taking the pooled standard deviation and dividing it by the square root of the sample size; thus, if the sample size is the same, then the standard error is the same.

The second factor that was examined was volume level. The results from the least squares mean comparison can be found in Table 4-30a. From this table, it can be seen that there is only one comparison that is significant, high to mid volumes with a p-value of 0.0027. In Table 4-30b, the least squares mean can be found for the high and mid volumes. It can be seen that the high volume has the lowest mean, while the mid has the highest mean value. The Tukey-Kramer p-value for the comparison between high and low was close to 0.05 but was not considered significant.

Table 4-30: Volume Level Least Squares Mean Comparison

a) Tukey-Kramer p-value

Volume Level (a)	**Volume Level (b)**	**Tukey-Kramer p-value**
High	Mid	0.0027
High	Low	0.0532
Low	Mid	0.4783

b) Mean, Standard Error, CI Values

			CI (%)	
Volume Level	**Mean (%)**	**Standard Error (%)**	**Lower**	**Upper**
High	88.9	1.80	85.3	92.4
Mid	95.9	1.66	90.4	96.9
Low	93.7	1.66	92.7	99.2

The final factor that was examined was speed limit. The results from the least squares mean comparison can be found in Table 4-31a. From this table, it can be seen that there is only one comparison that is significant, 35 mph and 40 mph with a p-value of 0.0207. In Table 4-31b, the least squares means can be found for the 35 mph and 40 mph speed limits. It can be seen that

35 mph has a least squares mean of 95.0, which is the third highest least squares mean but has the smallest standard error. The 40 mph speed limit has the lowest mean and the third smallest standard error. The possible reason that the third highest least squares mean was significant in comparison to the 30 mph and 50 mph approaches is the sample size. The sample sizes for 30 mph, 35 mph, and 50 mph are 12, 52, and 4, respectively. This shows that the 35 mph factor has the largest number of samples.

Table 4-31: Speed Limit Least Squares Mean Comparison

a) Tukey-Kramer p-value

Speed Limit (a)	Speed Limit (b)	Tukey-Kramer p-value
25	30	0.8079
25	35	0.9348
25	40	0.9826
25	45	0.9992
25	50	0.8960
30	35	0.9792
30	40	0.0773
30	45	0.1858
30	50	1.0000
35	40	0.0207
35	45	0.0883
35	50	0.9976
40	45	0.9899
40	50	0.2115
45	50	0.4005

Table 4-32: Speed Limit Least Squares Mean Comparison (Continued)

b) Mean, Standard Error, CI Values

Speed Limit	Mean (%)	Standard Error (%)	CI (%)	
			Lower	Upper
25	90.9	4.23	82.6	99.2
30	97.4	3.07	91.3	103.4
35	95.0	1.38	92.3	97.7
40	87.7	1.89	84.0	91.4
45	89.3	1.75	85.8	92.7
50	96.7	3.52	89.8	103.6

4.2.14 Test 14

Test 14 is the same as Test 13 except that the poorly performing 6-lane approaches are excluded for a total of six data points. For this test only three factors were examined: lane-by-lane, volume level, and speed limit. This test uses all the data that was collected for sensor position 1 except for the poorly performing 6-lane approaches, which are excluded. However, the main focus of this test was to see if there is a significant difference the farther an approach lane is away from the sensor as a whole. The results of Test 14 can be found in Table 4-33.

Table 4-33: Results from Test 14

Factor	p-value
Volume Level	0.0005
Lane-by-Lane	0.0225
Speed Limit	0.0110

On previous tests where all data were used, such as Tests 1 and 3, a full and reduced model was performed. However, in this case, no factor was insignificant enough to remove from the model to create a reduced model. As seen in Table 4-33, all three factors had p-values less than 0.05. To further examine the significant factors, a least squares mean comparison was performed for each of the significant factors.

The first factor examined was volume level. The results of the least squares mean comparison can be found in Table 4-34a. From this table, it is seen that there are two volume level comparisons that were significant. The first significant comparison was the high and mid volume levels with a p-value of 0.0293, and the second significant comparison was between the high and low volume levels with a p-value of 0.0003. In Table 4-34b the least squares mean for each volume level can be found. The lowest least squares mean corresponded to the high volume level, and the low volume level corresponded to the highest least squares mean.

Table 4-34: Volume Level Least Squares Mean Comparison

a) Tukey-Kramer p-value

Level (a)	Level (b)	Tukey-Kramer p-value
High	Mid	0.0293
High	Low	0.0003
Low	Mid	0.2942

b) Mean, Standard Error, CI Values

			CI (%)	
Level	**Mean (%)**	**Standard Error (%)**	**Lower**	**Upper**
High	88.3	1.80	84.8	91.9
Mid	93.6	1.69	90.3	99.8
Low	96.6	1.65	93.3	97.0

The second factor examined was lane-by-lane. The results of the least squares mean comparison can be found in Table 4-29a. From this table, it can be seen that there are two lane comparisons that are significant. The first comparison was between lanes 2 and 3 and lanes 2 and 5 with p-values of 0.0414 and 0.0411, respectively. The mean values that correspond to lane 2, lane 5, and lane 3 are the highest, second lowest, and the third lowest least squares means, respectively. The reason that the second and third lowest values were significant is most likely due to the sample size that corresponds to lane 3. Every sample included in this test has a minimum of 3 lanes because the smallest size intersection included in the study has 3 lanes. The standard error is also smaller than lane numbers larger than 3.

Table 4-35: Lane-by-Lane Least Squares Mean Comparison

a) Tukey-Kramer p-value

Lane (a)	Lane (b)	Tukey-Kramer p-value
1	2	0.434
1	3	0.883
1	4	0.9971
1	5	0.7608
1	6	0.8996
2	3	0.0414
2	4	0.2109
2	5	0.0411
2	6	0.2581
3	4	0.9912
3	5	0.9988
3	6	0.9988
4	5	0.9437
4	6	0.9744
5	6	1.0000

b) Mean, Standard Error, CI Values

			CI (%)	
Lane	**Mean (%)**	**Standard Error (%)**	**Lower**	**Upper**
1	94.1	1.94	90.3	98.0
2	98.8	1.94	95.0	102.7
3	91.3	1.94	87.5	95.2
4	92.9	2.04	88.9	96.9
5	90.2	2.43	85.4	95.0
6	89.7	3.92	82.0	97.4

The standard error for lanes 1, 2, and 3 are all the same because the sample sizes for these lanes are all the same. This is because the smallest intersections included in the study were 3 approach lanes. The standard error is calculated by taking the pooled standard deviation and dividing it by the square root of the sample size; thus, if the sample size is the same, then the standard error is the same.

The final factor that was examined was speed limit. The results from the least squares mean comparison can be found in Table 4-36a. From this table, it can be seen that there are no comparisons that are significant. This is likely due to the Tukey-Kramer numerical multiplier that is included in the least squares mean comparisons p-value. The Tukey-Kramer p-value adjustment is used for multiple comparisons and is an approximate test. Refer to Section 4.1.3 for further explanation. With this in mind, a comparison, 35 mph and 45 mph, is significant at the 90 percent confidence level with a Tukey-Kramer p-value of 0.0755, however is not at the 95 percent confidence level. This value suggests that the approach speed limit may affect the accuracy of traffic volume counts but it is inconclusive. In Table 4-36b, the least squares means can be found for all speed limits evaluated.

Table 4-36: Speed Limit Least Squares Mean Comparison

a) Tukey-Kramer p-value

Speed Limit (a)	Speed Limit (b)	Tukey-Kramer p-value
25	30	0.7166
25	35	0.8811
25	40	0.9989
25	45	0.9990
25	50	0.8187
30	35	0.9732
30	40	0.1564
30	45	0.1569
30	50	1.0000
35	40	0.1185
35	45	0.0755
35	50	0.9950
40	45	0.9999
40	50	0.6095
45	50	0.3380

Table 4-38: Speed Limit Least Squares Mean Comparison (Continued)

b) Mean, Standard Error, CI Values

Lane	Mean (%)	Standard Error (%)	CI (%) Lower	Upper
25	90.3	4.12	82.1	98.4
30	97.4	2.99	91.5	103.3
35	94.9	1.36	92.2	97.6
40	88.5	2.21	84.1	92.9
45	89.2	1.71	85.8	92.6
50	96.8	3.43	90.1	103.6

As previously mentioned, the speed limit factor was added midway thought the data collection and after the design of the project was decided. Thus, approaches that were chosen were to provide a robust sample size to the three original factors to be tested: number of approach lanes, volume levels, and sensor position. Because the speed limit factor was added towards the end of the project, and there was no time left to re-design the study with this factor, sample sizes for this factor vary in size and are dependent upon the originally chosen intersections. Thus, the speed limit factor is only for reference, and no definitive conclusions should be made based upon the findings from this study.

4.3 Chapter Summary

After data collection was completed, a total of 14 analyses were performed on the turning volume counts. A Mixed Model ANOVA was used to find factors that have significant impact on accuracy of volume counts. A least squares mean comparison was also performed to further understand how the different factors relate to one another within each data set. The results from the statistical analysis are useful to determine which factors are significant given different factor combinations. After all the analyses were performed, it was found that only one factor (sensor position) out of the four factors considered was not statistically significant at the 95 percent confidence level and hence had no significant impact on the accuracy of traffic volume counts. The remaining three factors, volume level, number of approach lanes, and speed limit, had an effect on the accuracy of volume counts. The following are the main findings from these analyses.

- When all data was analyzed, it was found that the number of approach lanes and the traffic volume level affect the accuracy of the counts for the SmartSensor Matrix at the 95 percent confidence level.
- When only 6-lane approaches were evaluated, it was found that the following two factors were statistically significant: lane-by-lane and volume level.
- When sensor position 1 data was evaluated, it was found that the volume level was the only factor that was statistically significant at the 95 percent confidence level.
- After all the analyses were completed, there was one factor that was never found to be statistically significant: sensor position.
- The lane by lane factor was found to only be statistically significant when 6-lane approaches were included in the analysis. However, the least squares mean comparison indicated that the statistically significant comparisons between lanes did not include lane 6.

The speed limit factor appeared a few times throughout the analyses as a significant factor, but its significance was not consistent. This is probably because the study was not initially designed to test the speed limit factor; the results on the speed limit factor were inconclusive. However, it was found that two factors, number of approach lanes and volume level, would affect the volume count accuracy in most of the cases.

The findings from this statistical analysis will be reflected in the practical application of the findings to meet the needs of UDOT to present accuracy levels in the SPMS website as presented in Chapter 5.

5 APPLICATION OF RESULTS

Once the analysis results were obtained and significant factors were identified, they were summarized for practical application in the SPMS. UDOT can provide these statistical values at each intersection. Among the four factors evaluated (number of approach lanes, volume level, sensor position, and speed limit), sensor position was found not to be a significant factor affecting the accuracy of traffic volume counts in any of the analyses and was therefore excluded for the application in the SPMS. The speed limit was also excluded because its effect on traffic volume count accuracy was not conclusive in multiple tests. A table showing the accuracy levels for the combinations of the two most significant factors is presented, along with an example for each of the tables in this chapter.

5.1 Volume Count Accuracy by the SmartSensor Matrix

This section looks at the accuracies of traffic volume counts in the combination of the two significant factors. Means and the 95 percent confidence intervals of the means are presented in Table 5-1, along with the standard deviation and sample size for each of the levels of all factor combinations considered. Table 5-1a provides the mean accuracy values for each combination, and Table 5-1b contains the 95 percent confidence interval of the means. Table 5-1c then shows the standard deviations of each combination. Table 5-1d shows the sample size of each factor combination. These tables include all the data that were collected, including the previously mentioned poorly performing 6-lane approaches. The actual number of samples in each factor combination is compared with the recalculated required number of samples based on different levels of acceptable error using the standard deviation obtained for each factor combination (see Table 5-1e). The results from this study can only be referred back to or used on similar intersections that have had qualified technicians complete a thorough QC/QA.

Table 5-1: Volume Level vs. Number of Approach Lanes

a) Mean Values By Factor

Number of Approach Lanes	Volume Level		
	Low (%) (Vol ≤ 100 veh/hr/ln)	Mid (%) (100 veh/hr/ln < Vol ≤ 250 veh/hr/ln)	High (%) (Vol > 250 veh/hr/ln)
2	100.8	101.0	100.1
3	99.8	98.5	98.7
4	97.1	95.9	94.7
5	94.6	92.6	89.2
6	95.3	84.2	82.5

b) 95 Percent Confidence Interval of the Mean

Number of Approach Lanes	Volume Level					
	Low (%)		Mid (%)		High (%)	
	Lower	Upper	Lower	Upper	Lower	Upper
2	97.6	103.9	97.3	104.6	95.3	104.8
3	97.5	102.0	94.6	102.5	97.4	99.9
4	94.1	100.1	91.7	100.1	90.8	98.6
5	91.9	97.2	88.8	96.3	80.3	98.0
6	93.8	96.8	79.7	88.6	74.9	90.2

c) Standard Deviation

Number of Approach Lanes	Volume Level		
	Low (%)	Mid (%)	High (%)
2	5.6	5.9	4.2
3	5.5	8.5	1.6
4	6.9	9.1	5.7
5	4.9	7.7	11.9
6	1.9	7.5	11.1

Table 5-1: Volume Level vs. Number of Approach Lanes (Continued)

d) Number of Samples Collected

Number of Approach Lanes	Volume Level		
	Low	Mid	High
2	12	10	3
3	23	18	6
4	20	18	8
5	13	16	7
6	6	11	8

e) Number of Samples Required

Number of Lanes	E = ± 5.0 %			E = ± 7.5 %			E = ± 10.0 %		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
2	6	6	2	2	2	*2*	*2*	*2*	*2*
3	4	12	*2*	2	6	*2*	*2*	3	*2*
4	8	12	6	3	6	2	2	3	*2*
5	4	10	22	2	4	10	*2*	2	6
6	*2*	10	19	*2*	4	8	*2*	2	5

Note: Number of samples *2* in italics was less than two when the number of samples required was calculated by equation (3-1). At minimum, two samples are needed to compute standard deviation.

Table 5-1a shows the means for each factor combination. As a general trend, the larger an intersection, or as the number of approach lanes increases, the less accurate the sensor data tends to be. Also, the higher the volume level is, the less accurate the sensor data tends to be. For example, four approach lanes with a mid-volume level having 100-250 veh/hr/ln have a mean of 96 percent accuracy, or, in other words, it counted 96 out of every 100 vehicles. Another example using a larger intersection of 6-approach lanes during a mid-volume level having between 100 and 250 veh/hr/ln, has a mean accuracy of 84 percent, or, in other words, it counted 84 out of every 100 vehicles. When these two examples are compared, the only difference between the two combinations is the number of approach lanes. By having two more approach lanes, accuracy decreases by 12 percent.

Table 5-1b shows the 95 percent confidence interval of the means shown in Table 5-1a for each combination of the two significant factors. This confidence interval of the mean indicates where the accuracy of the sensors will fall for the given factor level combinations. Many of the confidence intervals were found to have high accuracy in their counts. For example, using the same group from the previous paragraph, four approach lanes, and mid-volume level, the 95 percent confidence interval of the mean was found to be 92 to 100 percent. This indicates that 95 percent of the time, the mean value of accuracy, in percent, of the vehicles counted will fall somewhere within this confidence interval.

Table 5-1c shows the standard deviation for each of the factor combinations. The standard deviations ranged anywhere from 2 to 12 percent. Using the standard deviation, the 95 percent confidence intervals of the means shown in Table 5-1b were calculated. For instance, the standard deviation for the same factor combination mentioned above, that is, four approach lanes and mid-volume level, was 9 percent. The larger the standard deviation, the more spread out from the mean the data points were. This value does not indicate the distance away from 100 percent, that is, perfect match, or ground-truth data, but they simply indicate the level of accuracy distribution.

Table 5-1d shows the number of samples available in each factor level combination. The goal for the number of samples in each factor level combination was determined to be 7, as mentioned in section 3.2. For the most part, each group had 7 or more samples. As seen in Table 5-1e, there were a few factor combinations that did not meet the 7 sample goal, indicated by the yellow highlighted cells, based on the true standard deviations calculated after the data collection was completed. The amount of acceptable error allowed in this study affects the sample size needed to complete a robust statistical analysis.

When the level of error is 5 percent, there are only two combinations of factors that do not meet the minimum number of samples, 5- and 6-lane approaches with high levels of traffic volume. If the level of error were 7.5 percent, there is only one combination of factors that does not meet the minimum number of samples, 5-lane approaches. If the level of error were 10 percent, all combinations of factors would meet the minimum number of samples to complete a robust statistical analysis. The reason that there were not enough samples to complete the 5 percent error analysis is simply due to limited availability of that size of intersection equipped with the SmartSensor Matrix.

The values from Table 5-1 can be used as a base line to determine if the accuracy of a particular sensor is operating within an acceptable confidence interval based on the results from this research. When a signalized intersection has four lanes in the approach and the traffic volume is in the mid-level, the count values presented in the SPMS have an accuracy between 92 percent and 100 percent. For example, if a 4-lane approach intersection is being evaluated for its accuracy and the analysis was performed during a mid-volume level, values in Table 5-1 can be used. If the analysis resulted in an accuracy percentage of 93 percent, it can be said that it falls within the 95 percent confidence interval but was below the mean for this group.

5.2 Chapter Summary

This chapter presents the most important results from the study for practical use in the SPMS website in a table that shows accuracy ranges, given a combination of factor levels. The accuracy matrix allows the user to see the 95 percent confidence interval of the mean accuracy value for any given factor level combination, mean accuracy level, and standard deviation. The sample size for each factor level combination depends on the availability of studied approaches. An example was given to explain the meaning of the accuracy values found in Table 5-1, as well as an example of how to use the data presented in Table 5-1. Table 5-1b is the most important of the tables since it provides a range in which the mean accuracy values should fall with 95 percent confidence level. These results can help UDOT signal engineers to determine the accuracy of traffic counts that the SmartSensor Matrix would report to the SPMS based on the number of approach lanes and the traffic volume level.

6 CONCLUSIONS

The purpose of this study was to determine the accuracy of traffic volume counts reported by the Wavetronix SmartSensor Matrix. The preceding chapters have outlined the background; methods used to determine the accuracy of this sensor; results of statistical analysis; and recommended application of analysis results to the SPMS. A Mixed Model ANOVA was used to help determine which factors identified affected the accuracy of the sensor the most.

There were four factors—sensor position, number of approaches, volume level, and speed limit—to evaluate, which created a total of 14 tests performed on the data collected at various intersections across Utah and Salt Lake counties in the state of Utah.

The analyses performed indicated that two factors, number of approach lanes and volume level, influenced the accuracy of the traffic volume counts at the 95 percent confidence level. The analysis further indicated that sensor position had no effect on the accuracy of traffic volume counts obtained by the SmartSensor Matrix at the 95 percent confidence level. As for approach speed limit, effects on the accuracy of traffic volume counts were found to be inconclusive at the 95 percent confidence level.

This chapter summarizes the findings from the research and provides suggestions for future research.

6.1 Findings and Conclusions

There are many different types of traffic sensors available, both intrusive and non-intrusive. One type of traffic sensor is a radar-based sensor. Radar works off of the Doppler principle to locate and detect vehicles to gather data. The Wavetronix SmartSensor Matrix is a radar traffic sensor that is used by UDOT for its SPMS, is capable of vehicle detection through FMCW radar, and is evaluated in this study. It is paramount that the SmartSensor Matrix be installed following the manufacturer's instructions because initially the BYU team encountered multiple problems which all were a result of poor installation. During the sample data collection performed by the BYU team, it was found that some of the SmartSensor Matrix sensors were poorly aimed, which resulted in poor performance in traffic volume count. Through proper care in installation—following the minimum and maximum height requirements and angle of radar emittance—this microwave traffic sensor can properly function.

The number of samples that were needed for each factor level combination was decided based on a preliminary data collection, and then the data collection sites were chosen. The manual counts taken by the BYU research team were used as the ground-truth data in this study. Each vehicle was counted as the rear axle passed the stop bar, and each volume count lasted the duration of one hour. The data from the SmartSensor Matrix, called Hi-res data, were obtained from UDOT and reduced to determine the number of vehicles counted by the SmartSensor Matrix. To ensure accuracy of the data collection process, any manual traffic volume count, when compared to the Hi-res data, that was below 85 percent accuracy was revisited and its manual count was redone.

After data collection was completed, a total of 14 tests were performed on the traffic volume counts to have a detailed look into the data sets for potential sources that may give large differences. A Mixed Model ANOVA was used to find factors that have significant impact on accuracy of traffic volume counts. A least squares mean comparison was also performed to further understand how the different factors relate to one another within each factor level combination data set. The results from the statistical analyses were useful to determine which factors were significant given different factor level combinations. After all the analyses were performed, it was found that sensor position was not significant at the 95 percent confidence level and hence had no significant impact on the accuracy of traffic volume counts. Accuracy is defined by dividing the Hi-res traffic volume counts by the manual traffic counts. The following are the main findings from the study:

- QC/QA is an important step to obtain accurate data. Problems the BYU team encountered were attributed to the issues of QC/QA.
- It is important to note that the accuracy ranges given in Chapter 5 only apply to sensors that were installed and QC/QA properly performed by a trained technician.
- When all data were included, it was found that the number of approach lanes and the volume level consistently affect the accuracy of the counts for the SmartSensor Matrix at the 95 percent confidence level.
- The speed limit factor appeared a few times throughout the analyses as a significant factor, but its significance was not consistent and the results were not conclusive. This is probably because the data collection was not initially designed to test the speed limit factor.
- The lane-by-lane factor was found to only be statistically significant when 6-lane approaches were included in the analysis. However, the least squares mean comparison indicated that the statistically significant comparisons between lanes did not include approach lane number 6.

- As a general trend, as the volume level increases, the accuracy of the traffic count data decreases and as the intersections become larger, the accuracy of the traffic count data decreases.

A series of tables were created using the most significant factors to allow the user to see the mean accuracy values, the 95 percent confidence interval of the mean accuracy value, standard deviation, and sample size for a particular factor combination. The sample size for each factor combination changed depending on the availability of intersections for the group criteria. These results can help UDOT signal engineers to show the accuracy range in its SPMS, given the number of approach lanes and volume level, as shown in Table 5-1. The most important table among the tables in Table 5-1 is b. This table gives the 95 percent confidence interval of the mean accuracy for different factor combinations where the mean is expected to be with 95 percent confidence. To maintain the level of accuracy achieved in this study, proper maintenance of each SmartSensor Matrix must be performed periodically. Periodic maintenance will ensure that the sensors are aimed and functioning properly.

6.2 Further Research Recommendations

The research completed in this study is valuable in understanding the factors that can influence volume count accuracy of the SmartSensor Matrix. It is recommended that other factors not included in this study be tested to see if there are any effects on the volume count accuracy and the design of experiments set up properly. Factors to be looked at could include truck percentage, approach speed, roadway geometry, and virtual count zone locations, to name a few. Knowing which factors affect the volume count accuracy, measures can be taken to improve further the accuracy of traffic volume counts by the SmartSensor Matrix.

LIST OF ACRONYMS

ANOVA	Analysis of Variance
BYU	Brigham Young University
CW	Continuous Wave
CCTV	Closed Circuit Television
DET	Detector
FMCW	Frequency Modulating Continuous Wave
JTRP	Joint Transportation Research Program
ID	Identification
L	Left
NEMA	National Electrical Manufactures Association
QC/QA	Quality Control / Quality Assurance
R	Right
SAS	Statistical Analysis System
SPMS	Signal Performance Metrics System
SSMM	SmartSensor Manager Matrix
T	Through
TAC	Technical Advisory Committee
UDOT	Utah Department of Transportation
Veh/hr/ln	Vehicles per hour per lane

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APPENDIX A. RAW DATA

Table A-1: Raw Data

Intersection	Number of Approach Lanes	Sensor Position Number	Traffic Volume Level	Direction of Travel	Ground-Truth Counts	Hi-Res Counts	Ground-Truth Volume Per Lane	Percent Accuracy	Posted Speed Limit
Ashton Blvd & SR-92	2	1	Low	SB	111	111	56	100%	25
Ashton Blvd & SR-92	2	1	Mid	SB	465	484	233	104%	25
Ashton Blvd & SR-92	2	1	Mid	WB	210	203	105	97%	30
Ashton Blvd & SR-92	2	1	Mid	WB	412	412	206	100%	30
Ashton Blvd & SR-92	2	1	Mid	WB	211	203	106	96%	30
Ashton Blvd & SR-92	2	1	HI	SB	539	565	270	105%	25
Ashton Blvd & SR-92	2	1	HI	WB	858	832	429	97%	30
Ashton Blvd & SR-92	2	1	HI	WB	529	520	265	98%	30
University Ave & 4800N	3	1	Low	EB	282	298	94	106%	35
University Pkwy & Geneva, Provo	3	1	Low	EB	126	131	42	104%	Low
University Pkwy & Geneva, Provo	3	1	Low	EB	268	269	89	100%	Low
Geneva Rd & 1390N, Provo	3	1	Low	EB	61	54	20	89%	25
Main & 400S, Springville	3	1	Low	EB	284	290	95	102%	35
Geneva Rd & 800N, Orem	3	1	Low	SB	245	256	82	104%	45
Main & State, AF	3	1	Low	SB	155	143	52	92%	35
Main & 400S, Springville	3	1	Low	WB	220	221	73	100%	35
700W & 9000S. Sandy	3	1	Low	SB	162	171	54	106%	25
Geneva Rd & 800N, Orem	3	1	Mid	SB	484	482	161	100%	45
Geneva Rd & 800N, Orem	3	1	Mid	SB	607	585	202	96%	45
University Pkwy & Geneva, Provo	3	1	Mid	EB	611	595	204	97%	Low
Main & State, AF	3	1	Mid	SB	520	520	173	100%	35
Main & 400S, Springville	3	1	Mid	WB	479	478	160	100%	35
Main & 400S, Springville	3	1	Mid	WB	440	442	147	100%	35
University Ave & 4800N	3	1	Mid	EB	518	518	173	100%	35
Main & 400S, Springville	3	1	HI	EB	841	824	280	98%	35
Main & 400S, Springville	3	1	HI	EB	1157	1137	386	98%	35
2200W & 3500S, West Valley	4	1	Low	WB	267	265	67	99%	40
University Ave & University Pkwy, Provo	4	1	Low	SB	295	283	74	96%	35
University Ave & 300S, Provo	4	1	Low	EB	151	156	38	103%	35
University Ave & 300S, Provo	4	1	Low	SB	236	238	59	101%	35
University Ave & 300S, Provo	4	1	Low	WB	238	244	60	103%	35
University Pkwy & Geneva, Provo	4	1	Low	NB	123	119	31	97%	45
University Pkwy & Geneva, Provo	4	1	Low	NB	374	337	94	90%	45
University Pkwy & Geneva, Provo	4	1	Low	SB	159	138	40	87%	45

Table A-1: Raw Data (Continued)

Intersection	Number of Approach Lanes	Sensor Position Number	Traffic Volume Level	Direction of Travel	Ground-Truth Counts	Hi-Res Counts	Ground-Truth Volume Per Lane	Percent Accuracy	Posted Speed Limit
University Ave & 4800N	3	1	Mid	EB	518	518	173	100%	35
Main & 400S, Springville	3	1	HI	EB	841	824	280	98%	35
Main & 400S, Springville	3	1	HI	EB	1157	1137	386	98%	35
2200W & 3500S, West Valley	4	1	Low	WB	267	265	67	99%	40
University Ave & University Pkwy, Provo	4	1	Low	SB	295	283	74	96%	35
University Ave & 300S, Provo	4	1	Low	EB	151	156	38	103%	35
University Ave & 300S, Provo	4	1	Low	SB	236	238	59	101%	35
University Ave & 300S, Provo	4	1	Low	WB	238	244	60	103%	35
University Pkwy & Geneva, Provo	4	1	Low	NB	123	119	31	97%	45
University Pkwy & Geneva, Provo	4	1	Low	NB	374	337	94	90%	45
University Pkwy & Geneva, Provo	4	1	Low	SB	159	138	40	87%	45
Main & 400S, Springville	4	1	Low	SB	216	219	54	101%	30
Ashton Blvd & SR-92	4	1	Low	NB	293	245	73	84%	25
University Ave & 300S, Provo	4	1	Low	NB	305	307	76	101%	35
2200W & 3500S, West Valley	4	1	Mid	WB	826	820	207	99%	40
University Ave & University Pkwy, Provo	4	1	Mid	NB	411	424	103	103%	35
University Ave & 300S, Provo	4	1	Mid	EB	431	451	108	105%	35
University Ave & 300S, Provo	4	1	Mid	EB	797	810	199	102%	35
University Ave & 300S, Provo	4	1	Mid	NB	422	425	106	101%	35
University Ave & 300S, Provo	4	1	Mid	NB	450	452	113	100%	35
University Ave & 300S, Provo	4	1	Mid	NB	688	698	172	101%	35
University Ave & 300S, Provo	4	1	Mid	SB	685	674	171	98%	35
University Ave & 300S, Provo	4	1	Mid	WB	551	546	138	99%	35
University Ave & 300S, Provo	4	1	Mid	WB	761	665	190	87%	35
University Pkwy & Geneva, Provo	4	1	Mid	NB	679	595	170	88%	45
University Pkwy & Geneva, Provo	4	1	Mid	SB	407	350	102	86%	45
University Pkwy & Geneva, Provo	4	1	Mid	SB	782	648	196	83%	45
Main & 400S, Springville	4	1	Mid	SB	784	762	196	97%	30
Ashton Blvd & SR-92	4	1	Mid	NB	990	726	248	73%	25
2200W & 3500S, West Valley	4	1	HI	WB	1521	1518	380	100%	40
University Ave & University Pkwy, Provo	4	1	HI	NB	1144	1122	286	98%	35
University Ave & University Pkwy, Provo	4	1	HI	NB	1388	1361	347	98%	35
University Ave & University Pkwy, Provo	4	1	HI	SB	1018	904	255	89%	35
University Ave & University Pkwy, Provo	4	1	HI	SB	1270	1064	318	84%	35
University Ave & 300S, Provo	4	1	HI	NB	1269	1259	317	99%	35

Table A-1: Raw Data (Continued)

Intersection	Number of Approach Lanes	Sensor Position Number	Traffic Volume Level	Direction of Travel	Ground-Truth Counts	Hi-Res Counts	Ground-Truth Volume Per Lane	Percent Accuracy	Posted Speed Limit
University Ave & 300S, Provo	4	1	HI	SB	1584	1498	396	95%	35
Main & 400S, Springville	4	1	HI	SB	1227	1171	307	95%	30
700W & 9000S. Sandy	5	1	Low	EB	247	246	49	100%	50
700W & 9000S. Sandy	5	1	Low	WB	465	454	93	98%	45
2200W & 3500S, West Valley	5	1	Low	EB	493	468	99	95%	40
University Pkwy & Geneva, Provo	5	1	Low	WB	442	436	88	99%	45
Main & 400S, Springville	5	1	Low	NB	210	213	42	101%	30
Center & 500W	5	1	Low	NB	448	404	90	90%	35
University Ave & Eastbay	5	1	Low	EB	489	477	98	98%	Low
University Ave & Eastbay	5	1	Low	WB	494	483	99	98%	Low
Center & 500W	5	1	Low	EB	315	287	63	91%	35
7000S Redwood Rd	5	1	Low	EB	457	382	91	84%	35
7000S Redwood Rd	5	1	Low	WB	120	110	24	92%	35
7000S Redwood Rd	5	1	Low	EB	170	157	34	92%	35
700W & 9000S. Sandy	5	1	Mid	EB	946	916	189	97%	50
700W & 9000S. Sandy	5	1	Mid	WB	1109	950	222	86%	45
2200W & 3500S, West Valley	5	1	Mid	EB	1107	1116	221	101%	40
University Pkwy & Geneva, Provo	5	1	Mid	WB	508	504	102	99%	45
University Pkwy & Geneva, Provo	5	1	Mid	WB	645	636	129	99%	45
Main & 400S, Springville	5	1	Mid	NB	969	934	194	96%	30
Center & 500W	5	1	Mid	NB	828	683	166	82%	35
Center & 500W	5	1	Mid	NB	532	431	106	81%	35
University Ave & Eastbay	5	1	Mid	EB	599	590	120	98%	Low
University Ave & Eastbay	5	1	Mid	WB	653	575	131	88%	Low
Center & 500W	5	1	Mid	EB	1083	1064	217	98%	35
Main & 400S, Springville	5	1	Mid	NB	1239	1241	248	100%	30
7000S Redwood Rd	5	1	Mid	EB	531	431	106	81%	35
7000S Redwood Rd	5	1	Mid	WB	653	572	131	88%	35
700W & 9000S. Sandy	5	1	Mid	WB	941	950	188	101%	45
7000S Redwood Rd	5	1	Mid	WB	928	791	186	85%	35
700W & 9000S. Sandy	5	1	HI	EB	1991	1812	398	91%	50
700W & 9000S. Sandy	5	1	HI	WB	1891	1847	378	98%	45
700W & 9000S. Sandy	5	1	HI	EB	1483	1414	297	95%	50
Center & 500W	5	1	HI	EB	1488	1322	298	89%	35
Main & 400S, Springville	5	1	HI	NB	1528	1533	306	100%	30
7000S Redwood Rd	5	1	HI	EB	1370	884	274	65%	35
7000S Redwood Rd	5	1	HI	WB	1498	1296	300	87%	35

Table A-1: Raw Data (Continued)

Intersection	Number of Approach Lanes	Sensor Position Number	Traffic Volume Level	Direction of Travel	Ground-Truth Counts	Hi-Res Counts	Ground-Truth Volume Per Lane	Percent Accuracy	Posted Speed Limit
University Ave & EastBay	6	1	Low	NB	418	405	70	97%	35
University Ave & EastBay	6	1	Low	SB	466	433	78	93%	35
7000S Redwood Rd	6	1	Low	NB	296	287	49	97%	45
5400S Redwood Rd	6	1	Low	NB	372	349	62	94%	40
5400S Redwood Rd	6	1	Low	SB	490	363	82	74%	40
University Ave & EastBay	6	1	Mid	NB	1207	1170	201	97%	35
University Ave & EastBay	6	1	Mid	SB	1253	1173	209	94%	35
7000S Redwood Rd	6	1	Mid	NB	1062	919	177	87%	45
5400S Redwood Rd	6	1	Mid	NB	1275	1032	213	81%	40
5400S Redwood Rd	6	1	Mid	NB	1018	754	170	74%	40
Bangerter 13400	6	1	Mid	EB	1216	1134	203	93%	40
5400S Redwood Rd	6	1	Mid	SB	1387	943	231	68%	40
7000S Redwood Rd	6	1	Mid	NB	1185	1022	198	86%	45
University Ave & EastBay	6	1	HI	NB	1514	1324	252	87%	35
University Ave & EastBay	6	1	HI	SB	1703	1516	284	89%	35
5400S Redwood Rd	6	1	HI	NB	1732	1341	289	77%	40
Bangerter 13400	6	1	HI	EB	1683	1500	281	89%	40
5400S Redwood Rd	6	1	HI	NB	1730	1405	288	81%	40
5400S Redwood Rd	6	1	HI	SB	1790	1124	298	63%	40
State & 100E PG	2	2	Low	SB	121	122	61	101%	40
University Ave & Center, Provo	2	2	Low	EB	117	130	59	111%	15
700E 300S, Provo	2	2	Low	SB	107	106	54	99%	25
100N & 100E AF	2	2	Low	EB	154	152	77	99%	Low
State & 100E PG	2	2	Mid	SB	368	370	184	101%	40
100N & 100E AF	2	2	Mid	EB	259	249	130	96%	Low
University Ave & Center, Provo	2	2	Mid	EB	338	338	169	100%	15
900W & Center, Provo	3	2	Low	SB	214	208	71	97%	25
Pioneer Crossing & Mill Pond Rd.	3	2	Low	NB	120	106	40	88%	30
State St. & North Temple, SLC	3	2	Low	WB	234	218	78	93%	30
900W & Center, Provo	3	2	Mid	SB	352	363	117	103%	25
Geneva & Center, Orem	4	2	Low	NB	383	336	96	88%	45
Geneva & Center, Orem	4	2	Low	EB	29	27	7	93%	30
Geneva & Center, Orem	4	2	Mid	NB	697	639	174	92%	45
Ashton Blvd & SR-92	2	3	Low	EB	139	134	70	96%	30
100N & 100E AF	2	3	Low	WB	142	133	71	94%	Low
University Ave 100N	2	3	Low	EB	167	182	84	109%	25
University Ave 100N	2	3	Low	WB	132	137	66	104%	25

Table A-1: Raw Data (Continued)

Intersection	Number of Approach Lanes	Sensor Position Number	Traffic Volume Level	Direction of Travel	Ground-Truth Counts	Hi-Res Counts	Ground-Truth Volume Per Lane	Percent Accuracy	Posted Speed Limit
US-6 Canyon Rd	2	3	Low	NB	92	92	46	100%	45
State St. & 100E Lehi	2	3	Low	SB	176	176	88	100%	45
State St. & 100E Lehi	2	3	Low	NB	115	106	58	92%	45
Ashton Blvd & SR-92	2	3	Mid	EB	394	405	197	103%	30
Ashton Blvd & SR-92	2	3	Mid	EB	361	403	181	112%	30
100N & 100E AF	2	3	Mid	WB	253	240	127	95%	Low
400N State Orem	3	3	Low	EB	210	200	70	95%	25
400N State Orem	3	3	Low	WB	265	265	88	100%	25
US-6 & 800N SF	3	3	Low	SB	178	188	59	106%	Low
University Ave 800N	3	3	Low	WB	300	299	100	100%	25
700E 300S, Provo	3	3	Low	EB	225	235	75	104%	35
University Ave 800N	3	3	Low	WB	298	299	99	100%	25
1000S & Geneva, Orem	3	3	Low	EB	126	134	42	106%	25
University Ave & Canyon Rd	3	3	Low	WB	110	110	37	100%	35
400N State Orem	3	3	Mid	EB	600	529	200	88%	25
400N State Orem	3	3	Mid	WB	352	367	117	104%	25
US-6 & 800N SF	3	3	Mid	SB	391	428	130	109%	Low
US-6 & 800N SF	3	3	Mid	SB	374	412	125	110%	Low
700E 300S, Provo	3	3	Mid	EB	377	399	126	106%	35
State St. & North Temple, SLC	3	3	Mid	NB	664	657	221	99%	30
University Ave 800N	3	3	Mid	WB	489	370	163	76%	25
US-6 & 800N SF	3	3	Mid	SB	512	523	171	102%	Low
University Ave & Canyon Rd	3	3	Mid	WB	347	341	116	98%	35
700E 300S, Provo	3	3	HI	EB	922	930	307	101%	35
State St. & North Temple, SLC	3	3	HI	NB	1045	1029	348	98%	30
State St. & North Temple, SLC	3	3	HI	NB	1649	1649	550	100%	30
Geneva Rd & 800N, Orem	4	3	Low	WB	220	195	55	89%	35
Geneva & Center, Orem	4	3	Low	WB	288	320	72	111%	35
Geneva & Center, Orem	4	3	Low	WB	396	401	99	101%	35
US-6 & 800N SF	4	3	Low	NB	312	316	78	101%	Low
Center & 500W	4	3	Low	WB	375	354	94	94%	35
US-6 & 800N SF	4	3	Low	NB	309	316	77	102%	Low
Geneva Rd & 800N, Orem	4	3	Low	WB	225	227	56	101%	35
Center & 500W	4	3	Mid	WB	525	542	131	103%	35
Geneva & Center, Orem	4	3	Mid	WB	420	452	105	108%	35
SR 92 & 1200E	5	3	Low	NB	484	450	97	93%	25
5400S Redwood Rd	6	1	Mid	NB	1266	1037	211	82%	40

Table A-1: Raw Data (Continued)

Intersection	Number of Approach Lanes	Sensor Position Number	Traffic Volume Level	Direction of Travel	Ground-Truth Counts	Hi-Res Counts	Ground-Truth Volume Per Lane	Percent Accuracy	Posted Speed Limit
5400S Redwood Rd	6	1	HI	SB	1730	1047	288	61%	40
5400S Redwood Rd	6	1	Mid	SB	554	422	92	76%	40
700W & 9000S. Sandy	3	1	Low	NB	156	159	52	102%	25
State St. & North Temple, SLC	3	2	Mid	WB	440	369	147	84%	30
Main & State, AF	3	1	HI	SB	1137	1097	379	96%	35
Main & State, AF	3	1	Low	SB	198	198	66	100%	35
700E 300S, Provo	3	3	Low	WB	213	216	71	101%	25
7000S Redwood Rd	6	1	Low	NB	584	561	97	96%	45
7000S Redwood Rd	6	1	Mid	NB	1346	1092	224	81%	45
7000S Redwood Rd	6	1	HI	NB	2268	2111	378	93%	45