EVALUATION OF THE ACCURACY AND AUTOMATION OF TRAVEL TIME AND DELAY DATA COLLECTION METHODS

By

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DEDICATION

In memory of my grandmother, Ruth Benedict Plant.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Travel time and delay are among the most important measures for gauging a transportation system's performance. To address the growing problem of congestion in the US, transportation planning legislation mandated the monitoring and analysis of system performance and produced a renewed interest in travel time and delay studies. Current techniques for collecting travel time and delay data range from manual data logging to completely automated, computer-aided record keeping. The techniques employed by the University of Delaware have evolved into a semi-automated system, but human and computer error still have the potential to create inaccuracies.

In order to eliminate opportunities for human and computer error, a new GPS-based data collection technique was employed and compared directly with the currently accepted data collection methods. By simultaneously collecting data using three different techniques, the accuracy of the GPS positioning data and the resulting travel time and delay values could be objectively compared for automation and statistically compared for accuracy. It was found that the new technique provided the greatest automation requiring minimal attention of the data collectors and automatically processing the data sets. Using the Analysis of Means, Variances, Wilcoxon Signed Rank Test, and Pearson and Spearman Correlation Analyses, overall results showed that all data collection methods perform equally well for both travel time and delay time measurements.

Chapter 1

INTRODUCTION

1.1 Background

Travel time and delay are among the most important measures for gauging a transportation system's performance. These measures are easily understood by a wide variety of people, apply to nearly all transportation modes, and are used for a number of applications including congestion management (1). For these reasons, the US Department of Transportation (USDOT) and Federal Highway Administration (FHWA) require all state and local transportation entities to maintain travel time studies to quantify changes in mobility and congestion (2).

Travel time is defined as the time required to traverse a route between any two points. Its uses as a system performance measure are linked to its relationship among the other basic transportation parameters. Figure 1.1 shows a generalized representation of speed, density, and flow rate parameters. As vehicle flow increases to the optimum (critical) speed, the maximum density and maximum speed are reached (3). Beyond this point speed decreases and travel time is increased. This time that is accrued due to increased vehicle densities is frequently referred to as delay. Delay is frequently experienced as control delay, the effects of signalized and unsignalized intersections on interrupted flow corridors. Unlike travel time, however, the definition of delay varies from jurisdiction to jurisdiction. (3)

Throughout history, congestion increases have elicited a response to build new roads, widen existing roads, and overall provide increased capacity in the roadway network. "One of the most obvious advantages of constructing new or improved highways is that it results in a savings in time to people and freight traveling between areas served by the new or improved roadways" (4). Quantifying that savings in travel time is one of the first steps in the cost-benefit analysis of any highway project.

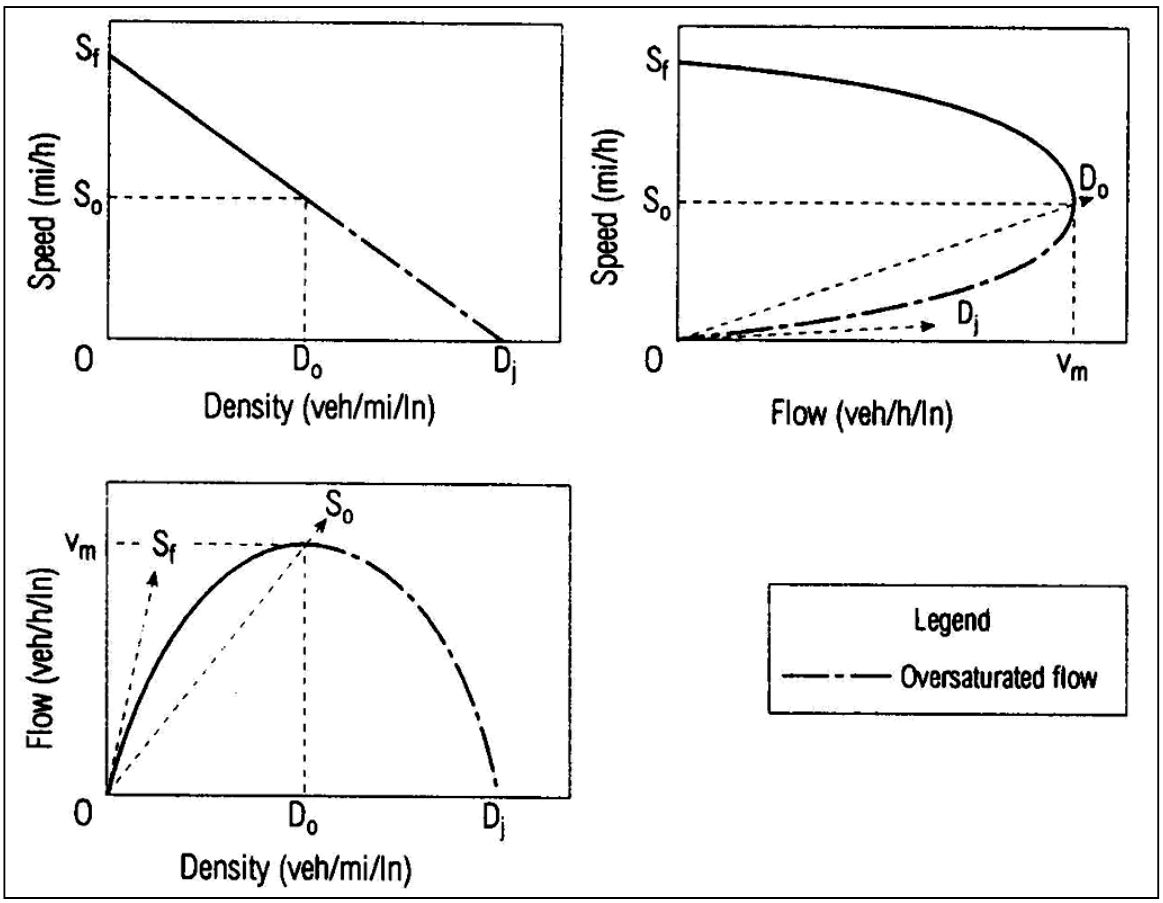

Figure 1.1: Speed, Density, and Flow Rate Relationships

[Referenced from Highway Capacity Manual, 3]

Because of travel time's importance in the increasing problem of congestion, in 1991 the USDOT posed a major change to transportation planning and policy with the release of the Intermodal Surface Transportation Efficiency Act (ISTEA). ISTEA mandated that a Congestion Management System (CMS) be developed for metropolitan areas with close coordination between the State DOTs and local Metropolitan Planning Organizations (MPO). A key feature of each CMS is a system for monitoring and analyzing of the entire transportation system's performance (5). Based on these recommendations, the passage of ISTEA produced a renewed interest in travel time and delay studies among DOTs nationwide.

There are a number of techniques available for gathering this fundamental data, but each technique exhibits its own benefits and detriments. Therefore each jurisdiction should determine the most effective and efficient method given their circumstances. The most common travel time data collection techniques are listed here (1):

1. Active test vehicle techniques,
2. License plate matching techniques,
3. ITS probe vehicle techniques, and
4. Non-traditional techniques.

Many of these techniques can be performed in a variety of ways ranging from manual data logging to completely automated, computer-aided record keeping. The final selection of a data collection technique is ultimately based on the intended location to be monitored. Features such as the initial costs, operating costs, accuracy, representativeness, sampling rate, and the amount of data processing required will determine the technique that is chosen (1). Because the features of each intended location may be dramatically different, it may be beneficial to select two or more techniques for different roadways.

Since 1997, the Delaware DOT (DelDOT) and the Wilmington Area Planning Council (WILMAPCO), with help from the Department of Civil and Environmental Engineering at the University of Delaware, have been using the Global Positioning System (GPS) application of the active test vehicle technique. This technique has been used throughout the state of Delaware and Cecil County, Maryland to collect the average speed, travel time, and delay time on all major collectors, arterials, and freeways as identified by DelDOT and WILMAPCO.

1.2 Problem Statement

Each travel time data collection technique is capable of measuring travel times within a range of degrees. Unfortunately, truly accurate travel time measurements are infeasible and therefore some degree of error is implicit within all data collection techniques available. Furthermore, some data collection techniques exhibit small errors incrementally. These errors tend to propagate throughout the entire data set compounding the problem with each passing mile. Over what distance is a small error acceptable when error propagation is of concern? Ultimately, what level of inaccuracy is acceptable?

Some techniques are also affected by human error. Inaccuracies in how the data collector perceives a given situation or errors in the manner the data is collected can cause an underestimation or overestimation in travel time and delay values. Furthermore, with the large amount of data and extensive processing, human error can be introduced easily due to carelessness, a calculation mistake, or a weak knowledge of the task (6). Is it possible to completely eliminate human error from the data collection process?

Additionally, the GPS test vehicle technique procedure practiced by the University of Delaware contains features that may present sources of inaccuracy. The measured routes are divided by "control points" into several segments in order to more precisely determine sources of congestion in the network. How accurately should these control points be determined to achieve more uniformity for each pass before it begins to affect accuracy too severely? Also, are these control points necessary in the analysis of the data at all?

1.3 Purpose and Objectives

The purpose of this thesis is to conduct a thorough investigation of the methods and assumptions used in the University of Delaware's current practice of collecting travel time and delay data. Every feature that may potentially create a source of inaccuracy or inconsistency will be scrutinized in an effort to make the data more representative of the true performance of the roadway network. As discussed, there are three primary sources of potential inaccuracy including data collection technique inaccuracies, human error related inaccuracies, and technique procedure method or assumption inaccuracies. To address these error sources, three different methods for the active test vehicle technique will be compared. The following objectives will be accomplished:

1. Examine each travel time and delay data collection method to determine which provides the greatest benefit to DelDOT and WILMAPCO.

2. Perform a detailed analysis of the possible sources of human error in an attempt to eliminate as many sources of error as possible for the preprocessing, data collection, and postprocessing phases.

3. Consider the specific features, methods, and assumptions adopted for this particular application of data collection will be performed.

4. Determine the optimal method for performing an active test vehicle travel time and delay data collection study with focus placed on automation and accuracy.

In the end, this information will serve to further advance Delaware's travel time and delay data collection program. It may also serve other jurisdictions with similar network conditions in search of a program to implement or a method for refinement of an existing program.

1.4 Scope

With the introduction of new computer techniques and applications, data collection and processing has evolved significantly over the past decades. New improvements have enabled transportation data to be collected with greater accuracy, frequency, automation, and productivity. This thesis will investigate the viability of the alternative active test vehicle travel time and delay data collection methods available and compare their performance with the methods presently accepted by state and federal transportation departments, councils, and organizations. The accuracy and automation of each method will be examined and compared using a number of statistical analysis methods.

1.5 Organization of Thesis

The remainder of this thesis will be organized as follows:

Chapter 2 will provide a literature review into the history of travel time and delay data collection. It also examines past studies conducted in the field of data collection automation as it pertains to travel time and delay studies. Finally, a history of the travel time an delay program at the University of Delaware will be presented.

Chapter 3 will discuss the travel time and delay study as it is coordinated presently. Points for improvement will be selected from the current procedures and an evaluation of the available alternatives will determine the ability of each to remedy those points for improvement.

Chapter 4 will provide an overview for the structure of the experiment conducted to evaluate the data collection method accuracy and automation.

Chapter 5 will describe the applications used for analysis and comparison of the data collection methods. The results of each analysis and a validation and verification of those results will be presented as well.

Chapter 6 will provide conclusions about the experimental methods, results, and overall completion of stated objectives. Also recommendations will be given regarding possible future studies to expand on this same theme and possible solutions not explored in this thesis.

Chapter 2

LITERATURE REVIEW

The concept of travel time as a means for evaluating roadway performance has been in place for almost as long as automobiles have been in production. Travel time alone serves as a fundamental quantitative measure, but it can also be used to compute other valuable congestion information like average speed and delay time. Its importance in traffic management is well documented and as a result, travel time data collection has been integrated into congestion management legislature for several decades. In the 1990s, travel time data collection became a mandate of the Intermodal Surface Transportation Efficiency Act (ISTEA) as part of each state's Congestion Management System (CMS) (5).

Like most other fields of transportation, seemingly unrelated technological advances have led to the advancement of transportation technologies. Travel time data collection is no exception. The active test vehicle technique began as a manual data collection method with the use of a test vehicle, stopwatches, and copious notes and calculations. This method relied heavily on human accuracy. Technology automated the process to a degree by linking the vehicle's transmission to a computer for data recording. However, this technology, known as the distance measurement instrument, presented unique problems in certain situations due to calibration needs.

The next significant advancement in the active test vehicle technique came about from the introduction of GPS into the public sector. GPS was originally realized by the US Department of Defense (DOD) for military use only. The GPS network was made available to the public in 1996, but initially the highest quality signal was reserved for military use only, and the signal available for civilian use, known as Selective Availability (SA), was intentionally degraded (7). On May 1, 2000, President Bill Clinton released a statement to discontinue the intentional degradation of SA: "The decision to discontinue SA is the latest measure in an on-going effort to make GPS more responsive to civil and commercial users worldwide. This increase in accuracy will allow new GPS applications to emerge and continue to enhance the lives of people around the world" (8). With this decision, the precision of GPS for civilian use was improved from about 100 meters to about 20 meters (7). Further developments such as Differential GPS (DGPS) and Wide Area Augmentation System or WAAS-enabled GPS receivers could collect the typical GPS positioning signals, but with correction codes that would greatly reduce errors incurred by atmospheric distortion. Typically, the position error of a DGPS position is 1 to 3 meters (9) and WAAS positioning typically provides better than 1 meter lateral accuracy (7).

Even with accuracies as low as 20 meters, GPS had the potential for application in a number of fields including transportation planning and traffic operations that rivaled the methods already in place. New developments are always evolving, giving way to more accurate and precise information.

2.1 Automation of Travel Time Data Collection

In recent years, a number of applications for GPS technology have led to innovative methodologies that have direct and indirect relevance to travel time data collection. Many of these experiments offer new ways of organizing and automating the data collection procedure.

In one such study, M. Hunter developed the Travel Run Intersection Passing Time Identification (TRIPTI) algorithm (10) for the collection and analysis of GPS-based travel time data. The TRIPTI algorithm was designed to capture travel time and delay experienced while traversing a road segment and the downstream intersection. Virtual reference lines were placed just past the upstream intersection and just past the downstream intersection to ensure proper assignment of the downstream intersection delay. The algorithm first checks each data point location against the known location of each intersection to determine which intersections were traversed. Then the algorithm determines the crossing time of the data point nearest the exiting reference line. An error check was also incorporated to identify vehicle speeds under 5 mph at reference lines as potential error.

Another study, created by A. Demers (11), was developed to create a real-time probe-based traveler information system. Probe vehicles equipped with a GPS receiver, a Pocket PC, a 3G wireless card, and CoPilot route guidance software gathered real-time travel time data that was used to make path choices for them by selecting the fastest route based on the real-time data from 200 vehicles (11). The speed and bearing data was collected using the GPS receiver which sent updates at regular intervals via the wireless card to a server that processed the data. The server then was able to use the data to determine the fastest route for upstream traffic and these new routes were relayed back to the drivers of the probe vehicles.

At 30 second intervals, each vehicle would transmit a "vehicle position" message describing the heading, speed, latitude, longitude, and time (11). While this information could be used to report travel time between two "vehicle position" points, organization of the collective 200 vehicle's data would be simpler if all vehicles were reporting data at common locations. To achieve this, a set of virtual landmarks called monuments were superimposed on the network (11). Every time a monument was passed, an "M_2M" message was transmitted. From the M_2M messages, segment travel times could be calculated to determine the fastest route for each driver. The information ascertained from these transmitted messages meet a number of the criteria required by travel time data collection.

Similar to Demers' approach to a more wide scale probe vehicle-based study, S. Shladover (12) developed a data sampling process as part of a vehicle-infrastructure integration (VII). Each VII-equipped vehicle on the road serves as a probe for data transmission. Snapshots are generated periodically to identify vehicle speed, vehicle stopping, vehicle starting, and other special events. These snapshots are collected by roadside receivers and compiled into a central database. "With suitable processing, these data can be turned into real-time indications of travel speed and volume, travel times, incidents, and weather and road surface conditions" (12).

2.2 History of UD/DCT/DELDOT Project

Since 1996, DelDOT with the help of the Civil and Environmental Engineering Department at the University of Delaware, has been measuring travel time and delay along most of Delaware's major collectors, arterials, and freeways. When the project was first established, data was collected using the manual active test vehicle technique. Manual data collection involved the use of stopwatches to measure the passage of time as a vehicle was driven along the corridor being studied. One stopwatch was used to measure travel time between control points and one stopwatch was used to measure the amount of time the vehicle traveled under 5mph. These values were hand-written on site and later manually recorded in spreadsheets for mathematical analysis. Because the manual method relied so heavily on human accuracy, a GPS application was adapted. The GPS data has proven to be at least as accurate as the data collected by conventional methods, and is 50% more efficient in terms of manpower. Annual reports documenting the data collection process, its applicability and accuracy, and the collected data have been compiled over the years.

In 2002, an analysis of GPS applications in traffic management systems was performed and published by Faghri and Hamad (13). Their analysis compared the performance of the GPS average vehicle technique against the manual average vehicle technique. A statistical study was performed to see whether significant differences existed between the two methods. Each method was used simultaneously to collect travel time and delay data with a sample size of 12 runs. Using an analysis of means and an analysis of variance, the travel time data proved to have no statistically significant difference between the means and variances.

In 2005, an additional evaluation was completed to compare the manual method and the GPS method to the outputs of a distance measurement instrument (DMI) (6). Under this experiment, all three methods were simultaneously collecting travel time, delay time, and distance with a sample size of 32 runs. Using non-parametric statistics, the data sets were evaluated in pairs by the Friedman Test, the Wilcoxon Signed Rank Test, the Sign Test, and the Minimum Chi-Square Test. The conclusions drawn are as follows:

1. Manual and GPS techniques perform equally well for travel time data.
2. DMI and GPS methods perform equally for delay time data.
3. Differences between the distance measurements provided evidence that Manual-GPS and Manual-DMI method pairs are not statistically different.

Based on the conclusions drawn from these precision analyses, GPS data collection was validated and became the primary method used for Delaware's travel time and delay study. Drawing a conclusion for statistical differences, however, was only one step to ensuring valid data was collected and reported to DelDOT annually. The proper sample size must be attained each year to be able to authenticate the validity of the data.

To address the concern of appropriate sample size, Faghri and Hamad performed an investigation into the number of runs required to maintain a confidence level of 95% (13). Data was collected on trip length, trip time, and delay time which was used to compute running speed. Based on the calculated values of the average range in running speed (5.0 mph) and information provided by ITE (see table below), the minimum number of runs was computed to be two (14).

Table 2.1: Sample Requirements with a Confidence Level of 95%

Average Range in Running Speed (mph)	Minimum Number of Runs for a Permitted Error of:				
	1.0 mph	2.0 mph	3.0 mph	4.0 mph	5.0 mph
2.5	4	2	2	2	2
5	8	4	3	2	2
10	21	8	5	4	3
15	38	14	8	6	5
20	59	21	12	8	6

2.3 Summary of Chapter 2

Travel time and delay play a fundamental role in traffic management as evidenced by the integration of travel time into CMS and other transportation legislation. The evolution of travel time data collection is largely due to technological advances and inventive applications. For many DOT and MPO jurisdictions, GPS has provided the best balance of flexibility and accuracy for the measurement of travel time and delay data.

As technology has created new avenues for advancement, a number of studies have been developed to explore automated methods of GPS use in both an active test vehicle technique and probe vehicle technique. The travel time and delay data collection project at the University of Delaware has undergone a similar evolution from a manual data collection method to a semi-automated method. Advancement to a fully automated method of data collection is the next step in the technological progression to greater degrees of accuracy.

Chapter 3

PROJECT OVERVIEW AND FUTURE NEEDS

This chapter will introduce the precise procedure currently used to collect travel time and delay data by the University of Delaware. This will be followed by analysis of possible points for improvement as the data collection method is further developed into a fully automated system. Additionally, an overview of the DOT and MPO needs of the project will be discussed, and the ability of replacement methodologies to meet those needs will be considered.

3.1 Project Overview

As mentioned, many travel time and delay data collection techniques can be performed in a variety of ways ranging from manual data logging to completely automated, computer-aided record keeping. The active test vehicle technique that is used by the University of Delaware has evolved over the years from a manual method, requiring a high degree of manpower, to a semi-automated method, involving GPS utilization.

Independent of the collection technique used, a number of experiment features must be defined prior to the field work of data collection. Objectives for the experiment must be clearly defined to ensure the proper result is achieved. Variables that will determine data collection scheduling, frequency, duration, and sample size must also be clearly defined based on the intended objectives.

3.2 Data Collection Methodology

The process of gathering travel time and delay data involves three primary steps: preprocessing, data collection runs, and postprocessing. These three steps were repeated with slight variations to be tailored to a Fall and a Summer project. However, prior to the formulation of a precise course of action, a comprehensive organization of the project was arranged to provide the strong foundation needed to reach a high level of accuracy. In order to proceed, the why, where, when, and how of data collection was established.

The "why" or the purpose of data collection can be explained by the typical trends in Delaware's traffic. The geographical location of the state places it in the unique situation of catering to the travel needs of its own residents in population centers like Wilmington, Newark, and Dover, and to the travel needs of those traveling along the Interstate 95 corridor between Philadelphia and Baltimore. These characteristics come together to create unstable traffic conditions during rush hour periods. The Fall travel time and delay data collection project was created with the primary goal of measuring the ability of the Delaware roadway network to manage the high demand impressed upon it during these peak hour periods. Essentially, it consists of an analysis of the network's performance during morning and evening rush hour. The state of Delaware also hosts thousands of beach-goers from Delaware, New Jersey, Pennsylvania, and Maryland. Many of the most popular beaches in and around Delaware create unstable traffic conditions during weekends. The Summer project was created to monitor the performance of the network to handle these beach-going traffic conditions.

The intended recipient of the data also played a significant role in its purpose and design. Because these data collection programs were created to meet the needs of WILMAPCO and the planning division of DelDOT, analysis is geared toward a more macroscopic view of the network. It is not intended to provide a microscopic view into features such as signal timing performance or turning movement lane capacity.

Next, the “where” or the location is determined. The chosen purpose has provided a broad scope for the study area, but specific roadways were selected for study. In this particular case, DelDOT and WILMAPCO have selected many of the major and minor arterials, collectors, and freeways in the areas of interest. For Fall analysis, most of the radial and circumferential arterials and collectors surrounding major trip generating land uses are included with special emphasis in the areas of Newark, Wilmington, and Dover, Delaware. For Summer analysis, most of the major Sussex County East-West routes and statewide North-South routes are included as they provide the most direct access to the beach areas.

Though it may seem simple enough to select times for data collection, this “when” feature of the design is vital. The most challenging time a roadway will face will be the peak hour of its regular week to week flow pattern. Our selection of ideal peak hour times involved analysis of automatic traffic recorder (ATR) data. These ATRs scattered around the state on a number of its important arterials and collectors are able to provide a detailed record of volume on roads in five minute intervals 24 hours a day and

365 days a year. From this ATR data the average commuter peak hour can be selected for Fall data collection. Based on the ATR data, morning peak hour was determined to occur between 7:00AM and 9:00AM and afternoon peak between 4:00PM and 6:00PM.

With regards to Summer data collection, an investigation was conducted to determine the peak hours experienced on roadways. This study involved numerous interviews with business owners and beach house landlords about their experiences with area traffic (15). The conclusions drawn from the study state that the majority of beach-goers travel to and from the shore points on Friday afternoons, Sunday afternoons, and throughout the day on Saturday. Traditionally, data has been collected heading toward the beach (southbound and eastbound) on Friday evenings from 3:00PM to 7:00PM and on Saturday mornings from 9:00AM to 12:00PM. Data was also collected heading away from the beach (northbound and westbound) on Saturday evenings from 4:00PM to 8:00PM and on Sunday afternoons from 4:00PM to 7:00PM. In 2006, a detailed analysis was conducted to determine the peak hour for Summer data collection. Recommendations for this revised methodology were provided by the Delaware Center for Transportation (15) and can be found in Table 3.1.

From this point, the "how" of the three phases of preprocessing, data collection runs, and postprocessing can be explained.

Table 3.1: Recommended Data Collection Intervals on Saturdays

Route	Direction	Beginning Segment	Start Time
SR 1	SB	SR 141	9:00–10:00am
	NB	SR 54	4:00-5:00pm
US 113	SB	SR 1 Split	11:00am-12:00pm
	NB	Maryland State Line	4:00-5:00pm
US 13 (Wilmington to Dover)	SB	I-495	9:00–10:00am
	NB	SR 1/US 113 Split	4:00-5:00pm
US 13 (Dover to MD Line)	SB	SR 1/US 13 Split	9:00–10:00am
	NB	SR 54	4:00-5:00pm
SR 404	EB	Maryland State Line	10:00–11:00am
	WB	SR 1	4:00-5:00pm
SR 16	EB	Maryland State Line	10:00–11:00am
	WB	SR 1	4:00-5:00pm
SR 36	EB	SR 404	10:00–11:00am
	WB	SR 36/16 Split	4:00-5:00pm
SR 20	EB	Maryland State Line	10:00–11:00am
	WB	SR 1	10:00–11:00am
SR 24	EB	Maryland State Line	9:00–11:00am
	WB	SR 1	4:00-5:00pm
SR 26	EB	SR 54 Split	9:00–10:00am
	WB	SR 1	4:00-5:00pm
SR 30	SB	SR 1	10:00–11:00am
	NB	US 13	4:00-5:00pm
SR 1D	SB	US 9	10:00–11:00am
Plantation Rd	NB	SR 1	4:00-5:00pm
SR 5	SB	SR 1	10:00–11:00am
	NB	Indian River Bay	4:00-5:00pm
SR 54	EB	Maryland State Line	9:00–10:00am
	WB	SR 20	4:00-5:00pm

3.2.1 Preprocessing

The preprocessing stage involves the organization of much of the project. While GPS data will be collected every second along the trip, that data must be clustered in a way that makes its presentation more manageable and useful for transportation planners. For this reason, each route that is studied is subdivided into small portions called segments. Each segment can vary in length, but is always preceded and followed by a control point. Control points are used to designate significant positions in the route where vehicles are introduced to or removed from the traffic stream or where the functional classification of the route changes. By this method of separation, all portions of each segment are of a similar functional classification, though two or more intersections are frequently contained in a single segment.

With each route's control points defined, this information is logged into the computer software used for data collection. Using Trimble's TerraSync software, data dictionary files are completed for each route. Data dictionary files preset features and attributes for each route that can later be applied during a data collection run. For each route, there are two kinds of features that may be applied: a control point feature and a delay point feature. When applying features to a route, those features require further descriptive measures called attributes. For control point features, three attributes are able to be applied: the control point name, the direction of travel, and the weather conditions. The control point name attributes are preloaded as those control points already determined. For delay point features, two attributes are able to be applied: the reason for delay and the location of the delay. The delay reason attributes are preloaded for any possible sources of delay such as toll, construction, congestion, railroad crossing, pedestrian crossing, traffic signal, left turning vehicle, bus stop, stop/yield sign, accident, and emergency vehicles. The final step in preprocessing the software program is loading a background map of the entire roadway network. This map assists in the data collection by providing a visual confirmation of the vehicle's location.

3.2.2 Data Collection Run

The data collection stage involves two or more people traversing the route to be studied in a vehicle equipped with a GPS receiver and laptop. A minimum of two people are required to maximize safety and accuracy during the data collection run. The first individual is responsible for operating the vehicle. This responsibility includes mapping the anticipated course for navigational purposes, exercising defensive driving practices for safety, and maintaining a speed comparable to that of the average driver on the road. The second individual is responsible for operating the laptop and ensuring data collection is performed accurately. With a Trimble GPS Receiver, a laptop preloaded with Trimble's Terrasync software and predefined data dictionary files, and printed road maps, data collection may begin.

Before the vehicle has reached the start point, or the first control point, the second individual prepares the laptop and GPS receiver for data collection by creating a new file for the data to be stored and by selecting the data dictionary file to be used. Terrasync begins collecting data second by second as soon as a connection with the GPS satellites is secured. From this point, the individuals in the car must simply continue on course creating control point and delay features where necessary. At the preset control points, the second individual is responsible for initiating control point features as the vehicle crosses through the center of the intersection or interchange and concluding the feature at the next control point. Delay features must also be created at any point the vehicle's speed drops below 5 mph. Following the final control point, the file is closed to conclude the collection of data from the satellites.

This process is repeated for each individual run. If human or technology errors occur, causing an inaccuracy, the run must be restarted from the last accurately recorded control point. In some cases, however, technological error is caused by a loss of contact with the GPS satellites. Satellites are occasionally taken offline without warning by the Department of Defense, therefore data collection must sometimes be conducted using a less automated, manual technique as described previously. Given a successful run using the GPS method, each run will yield a second by second record of the route's latitude, longitude, speed, bearing, inclination, and corresponding time stamp.

3.2.3 Postprocessing

During the postprocessing phase, the output files from the data collection run are manipulated to yield the data that is desired by DelDOT and WILMAPCO. Before calculations are performed, however, any reparable errors in the data recording process are corrected at this time. Reparable errors include the correction of mislabeled features and attributes. In the event that data collection was interrupted and had to be resumed from the last accurately recorded control point, the resulting output files would then be spliced together to reflect the complete route traveled as though no interruption had occurred. Following these minimally invasive corrections, final calculations are executed.

The output data yield several important pieces of information that are compiled into a tabular format for presentation purposes. Those values that are calculated from the data collection output include:

- Mean Travel Time – The average time in seconds that was taken to travel the length of the segment during the peak hour.

- Mean Travel Speed – The average speed of the test vehicle traveling from one control point to the next during the peak hour. This value is obtained by dividing the distance of the segment by the mean travel time.

- Total Delay – The time spent in delay traveling through the given segment during the peak hour. By DelDOT's definition, delay is the time when vehicle's speed drops below 5 miles per hour.

- Mean Running Speed – The average speed that a vehicle would travel through the route segment if delay were not experienced. This value is obtained by the following equation:

$$\text{MRS} = \frac{\text{Distance}}{\text{Mean Travel Time - Total Delay}}$$

- Percent Time in Delay – The percentage of time spent in delay for that route segment. The percentage is obtained by dividing the total delay by the mean travel time, then multiplying the quantity by 100.

$$\text{Percent Time in Delay} = \frac{\text{Total Delay}}{\text{Mean Travel Time}} \text{x } 100$$

- Level of Service (LOS) – LOS is a quality measure describing operational conditions within the traffic stream. The LOS is determined based on the percent difference between the weighted average posted speed and the mean travel speed. The weighted average posted speed is determined based on the posted speeds and the number of miles they apply to within a segment. Therefore the LOS is based on the difference between the ideal case of traveling at the posted speed through the entire segment and the actual case of traveling through intermittent delay. The distinction from LOS A through LOS F are as follows:

Table 3.2: Level of Service Guidelines

Level of Service	Percent Difference
A	<10%
B	10% - 30%
C	30% - 45%
D	45% - 60%
E	60% - 70%
F	>70%

The resulting data table is then used to populate a Geographic Information System (GIS) database where further analyses and maps can be generated based on future requests for information.

3.3 Points for Improvement

As previously mentioned, the active test vehicle technique that is used by the University of Delaware has evolved over the years from a manual method to a semi-automated method, involving GPS utilization. The older manual method required a high degree of manpower and relied heavily on human accuracy. With the introduction of GPS, an electronic record of the route traveled could be accurately documented, though much of the organizational features, such as control point and delay point logging, still depended on human accuracy. Though GPS integration has provided a greater degree of automation, a number of points for improvement remain.

These points for improvement are possible sources of inaccuracy caused by both human error and software inadequacies. In some cases, the human error problems can be solved by data collectors directing more of their attention to the task at hand and away from distracters while on the road. However, if these same problems can be corrected by providing further computer automation, that would be the preferred remedy. Overall, points for improvement have been found in each portion of the methodology, but as would be expected, the large majority of them affect the data collection run portion of the project.

3.3.1 Preprocessing Improvements

Initially, the project begins with preprocessing. Very few sources of inaccuracy have been found in this portion of the project simply because it is difficult to accrue inaccuracies before data is actually collected. The selection of control points, however, has been shown to create inaccurate features within the data. Inaccuracies do not occur at every control point, but a limited number of control points are too vaguely defined to yield the same precision as other, less ambiguous control points. A prime example for this occurs at the interchange between SR 1 and US 13 in the vicinity of Tybouts Corner, DE (Figure 3.3). Normally the control point would be logged at the overpass of the two highways, a characteristic typically found in a cloverleaf or a diamond interchange. Because SR 1 and US 13 form a trumpet interchange, this defining overpass characteristic is not present for all directions of travel. This leads to inconsistencies between data collection runs where two different data collectors may interpret the control point's location differently. In the future, a common point will need to be chosen to eliminate this point of confusion.

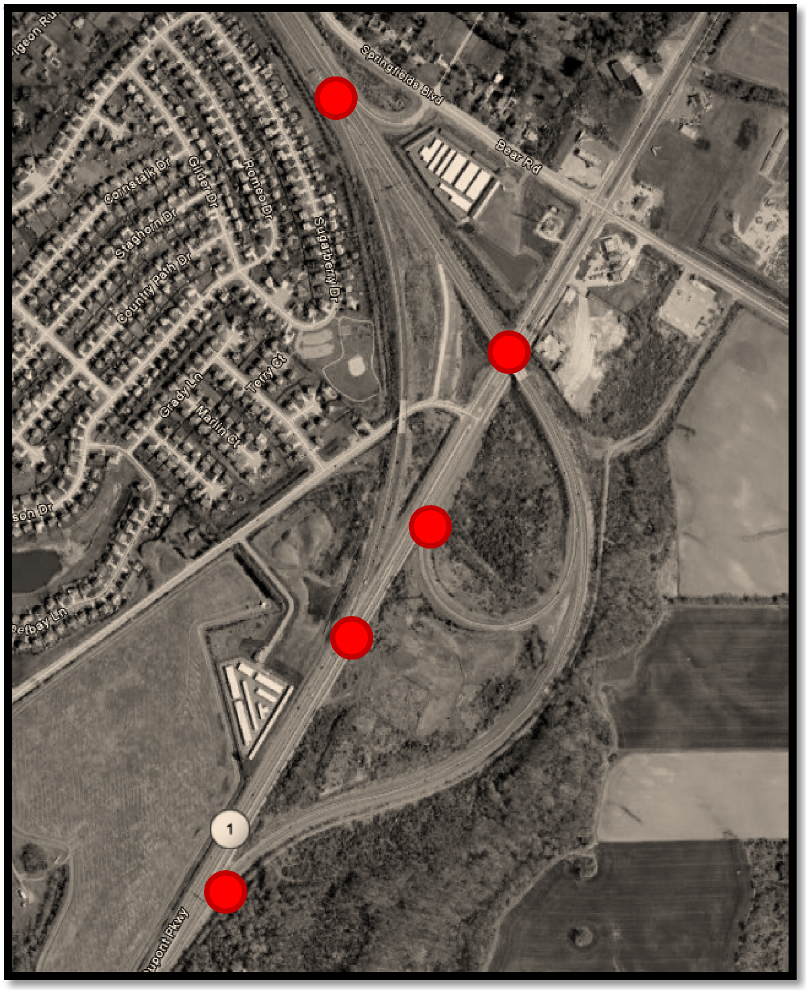

Figure 3.1: SR 1/US 13 interchange with possible control point options

3.3.2 Data Collection Run Improvements

Following the preprocessing stage, the data collection run exhibited the largest number of points for improvement. Most of these problems are human error related, but a number of them are due to software limitations and inadequacies as well. As stated, human error is usually the result of a lack of attention being paid by the data collector, but eliminating a person's susceptibility to distraction is arguably impossible. This distraction most frequently results in missing control point and delay feature logging. When a control point is not logged, the postprocessing procedure to repair this error is amplified a great deal. The latitude and longitude of the point must be determined and identified among a list of data points from every single second along the route. When a delay point is not logged, its exact location cannot be reproduced nor can the source of delay be identified for postprocessing. These functions are features to look for in any computer software upgrades for the future.

Unfortunately, the current software package used is not capable of recording these control point and delay features independent of a human prompt. Control point features are recorded as a "line" feature, but the output file for that line feature does not include vital information like latitude/longitude positioning, distance traveled, or travel time. Furthermore, delay features are recorded as a "node" feature, but the output file lacks information like latitude/longitude. These inadequacies also increase the amount of postprocessing required to determine location, distance, and travel time information.

Control point and delay point logging is further disrupted by the software's inability to nest these objects. Nesting refers to the simultaneous recording of two different features. In the past, the control point line features were interrupted so that delay point features could be logged when necessary. This was found to incur a time stamp error during the postprocessing of the data that had to be manually remedied using the known latitude/longitude information for each control point.

Sources of inaccuracy also occur when the data collector's attention has not been compromised. As mentioned, DelDOT and WILMAPCO define delay as any point the vehicle's speed is below 5 miles per hour. Currently, the process for identifying delay involves monitoring the vehicle's speedometer. On many vehicles, the speedometer does not show significant detail, particularly for speeds below 10 miles per hour. Based on this process, delay is sometimes not recognized and sometimes incorrectly identified. Ideally the vehicle's speed changes would be identified using the GPS receiver. If the computer software were able to identify critical speed changes and prompt the data collector for information like street location and delay reason, these missed and incorrect delay nodes would be avoided completely.

Unlike the previous examples, error sources do not originate from the data collector alone. The driver of the vehicle also affects the presence of error in the data collection process. The most critical mistake a driver can make is to make a wrong turn. Wrong turns require the team to back track to the last accurately recorded control point and start recording again. This can make finishing data collection within the prescribed time period challenging. Also, stitching the separate files together increases postprocessing time and energy. Because GPS receivers are so prevalent in the commercial market for directional uses, it may be possible to find a software or hardware that will collect the necessary data and direct the driver visually and/or audibly throughout the trip.

3.3.3 Postprocessing Improvements

The final step, postprocessing, can often be the most susceptible to errors. During this period, the raw data is edited in excel spreadsheets. Because the editor is handling so many files and performing calculations of a very repetitive nature, the possibility of carelessness or a calculation mistake could cause damage to the entire data set. A software program that output these important values automatically would save time and energy during postprocessing, as well as removing a significant chance for error.

In addition to the calculated data sheets, the data is displayed in a GIS format for mapping purposes. Importing this data from their respective excel spreadsheets to line segments in a GIS environment is a time-consuming process and requires a great deal of energy. Because these GIS maps are a secondary target for the project, finding a GIS-compatible software will not become a priority for this study. If GIS compatibility can be found in a program that remedies as many points for improvement as possible, it will take preference over other alternatives, but GIS compatibility will not be recommended at the expense of other problem resolutions.

3.4 Discussion of MPO and DOT Needs

At the regional scale, WILMAPCO, the region's MPO, is responsible for identifying and addressing congestion in the areas of New Castle County, Delaware and Cecil County, Maryland. This analysis is performed using a number of parameters and data sets including the travel time and delay data collected by the University of Delaware. Annually WILMAPCO releases a CMS report for public and private audiences presenting their analyses and findings. This report is intended to illustrate the dynamics of the area's congestion by highlighting the regional impacts caused by slight and seemingly isolated changes in the transportation network as a whole (16). A series of performance measures have been assembled for the region's evaluation. The performance measures used by WILMAPCO in congestion identification analysis include (16):

- Roadway volume to capacity ratio (daily)
- Intersection Level of Service (peak hour)
- Roadway Travel Speeds vs. Posted Speed Limit (AM/PM peak)
- 3-year Crash Rate (intersection and road segments)

The travel time and delay research conducted by the University of Delaware serves as the sole information source for WILMAPCO's third performance measure, travel speed versus posted speeds, or percent under posted speed. Specifically, this measure compares the average vehicle operating speed to that of the posted speed for a given segment. While travel speed and delay are only easily understood when the characteristics of the roadway are known, the percent difference between average and posted speeds can be compared year to year without additional contextual information.

Additionally, WILMAPCO releases a data report containing trend mapping analysis of the travel time changes in the region. This report takes a macroscopic view of travel time and delay in the study area. Macroscopically, the travel speeds and delays are averaged over all routes and presented for trend analysis from year to year. Key corridors are also analyzed with travel time and travel speed averaged across the entire route and cross referenced with other information such as Annual Average Daily Traffic (AADT), population change, and employment change (17).

Overall, WILMAPCO can benefit the most from accurate data collection at the peak hour periods of interest. These data should be presented in a variety of ways, including figures that the general public can understand with minimal explanation. While the current methods have been catering to these needs, it is imperative to maintain these same standards. Additionally, however, it is worth considering that trend analysis would be less accurate if a new method proved to yield statistically different values than the current method. Past years of data could be incompatible with new data resulting in inaccurate trend analyses.

At the state-wide scale, DelDOT's Planning Division has jurisdiction in New Castle, Kent, and Sussex Counties and is responsible for providing transportation information and advice to local governments and solving transportation problems by collecting and analyzing transportation related data. Travel time and delay data is only one set of data that DelDOT receives annually, however, it plays a vital role in the understanding of Delaware's changing travel patterns. DelDOT uses travel time and delay data to determine the most congested roadway segments in the network. This information can then be relayed to local governments that may then affect future land use changes that will in turn affect the transportation network. Concerns about particular problems in the network are also brought to the Transportation Solutions Division for developing viable remedies to the causes of congestion.

3.5 Preliminary Evaluation of Alternatives

In the search for a new method for travel time and delay data collection, it was essential to find alternatives that would address the maximum number of error sources while still delivering the data in a manner that best suits the MPO and DOT needs. Several viable alternatives were considered, but of all the travel time and delay equipment and software packages available, the following four were chosen for greater consideration as they were marketed as being useful for travel time applications:

- ESRI ArcPad 8
- Magellan Professional MobileMapper 6
- PC-Travel Software Suite 2
- GeoStat TravTime 2.0

Upon initial inspection of each alternative, it was found that while ESRI ArcPad and Magellan MobileMapper were both extremely powerful pieces of equipment, these systems were designed with flexibility for multiple applications. Unfortunately that flexibility frequently limited the amount of automation that was possible using those systems. The remaining two systems lack the flexibility found in ArcPad and MobileMapper, but because they are so specialized, they are able to provide the highest level of automation to a travel time and delay data collection project.

The manner in which the new systems collect data is quite different from the current system. As discussed, the current system requires a data collector to input features and attributes along a route while the GPS receiver logs second by second position and velocity data. This interactive process is performed on a laptop with preloaded programs for data collection and route features and attributes to simplify the data collection process somewhat. The data is collected in separate routes and separate runs of each route must be subdivided manually. Following data collection, the data is exported and human error mistakes are corrected by hand.

The new systems require no human interaction to perform their duties. In the case of the TravTime software, the GPS antenna is placed on the roof of the vehicle, the data logger is wired to the antenna, and the units are supplied power via the vehicle's cigar lighter receptacle. The data logger is a small unit called a GeoLogger that is responsible only for storing data. At this point, the vehicle is driven from the beginning control point to the ending control point mimicking the performance of the average driver. During this time TravTime's data logger is silently logging second by second position, time, date, speed, heading, altitude, HDOP, and satellite data. The data logger unit provides only one indication of its performance through an LED indicator that gives information about the device's status based on the sequence of flashes. Several routes may be collected consecutively until the device's memory capacity has been reached. Following data collection, the data is imported into the postprocessing software where the routes are automatically extracted and split at their respective control points according to preloaded control point position data.

PC-Travel operates in a very similar way to TravTime with a few exceptions. PC-Travel does not have a designated data storing unit and simply utilizes a laptop or PDA. This enables the data collector to view the status of the unit continuously throughout the run. Once the data is collected and ready to be post processed, there are no capabilities to preload control point position data therefore the routes must be trimmed by hand for each individual run.

The TravTime system is able to eliminate a number of error sources related to the current system. Issues related to ambiguous control point locations and missed or duplicated control points are completely eliminated by removing the human element. By supplying the software with the latitude and longitude of the points of interest, all processing of the data is done by the computer. This also reduces the amount of postprocessing fatigue that is experienced by the human data processor as much of the work is done by the software itself. It is expected that as the data processor experiences fewer repetitive motions, closer attention will be paid to the accuracy of their manipulations. Postprocessing fatigue will also be reduced in the GIS processing stages as the processing software is already compatible with ESRI's GIS software (18). While PC-Travel also eliminates the problem of ambiguous, missed, and duplicated control points, postprocessing fatigue still persists as the start and end points of each route must be trimmed by hand. The control points along the route also must be established in each new project rather than having preloaded route profiles readily available.

While a number of very important problems may be resolved under both new systems, some error sources are left unchanged and some new problems become apparent. Delay feature locations are now logged and automatically compiled, however additional information must still be recorded by hand. Information such as a delay's source will always require active qualitative interpretation of a situation through a data collector's eyes. The data alone can only differentiate between one isolated instance of stopping and repeated stopping such as bumper to bumper traffic. It is not sophisticated enough to identify delay caused by a pedestrian crossing versus a signalized intersection. Therefore, the data collector still needs to be able to identify when delay has been reached in order to record the necessary observations. Because the data logger has no interactive features, there is still no method for accurately alerting the data collector that the vehicle's speed has dropped below 5mph.

In the case of the TravTime data logger, its lack of interactivity also presents concerns regarding the device's status during data collection. The only way for the data collector to diagnose a problem with the data logger is to visually inspect the LED flashing sequence periodically throughout the trip. While the sequences provide for warnings such as low battery life and low memory, there is no indication of failure for a satellite connection to be secured or any other cause for concern. At times a data collector may also be interested in knowing the number of satellites the receiver is using for triangulation to determine how accurate the positioning may be at any point during the run. This information can be ascertained during postprocessing, but it could also be useful in determining the unit's connection status in the field. This greatly reduces the data collector's likelihood of noticing a problem and ability to troubleshoot the system in the field. An audio cue may be preferred to ensure attention is brought to the problem and a more extensive list of troubleshooting notifications should be provided. PC-Travel, on the other hand, utilizes a laptop or PDA and displays its status during the trip thereby eliminating interactivity concerns.

The final error concern related to wrong turns during data collection also is not addressed by the new systems. This problem may be very easily remedied by providing an independent consumer-grade GPS unit that is responsible for providing visual and audible turn by turn directions to the driver of the vehicle. Many manufacturers produce models that allow specific routes to be programmed for easy repetition.

Overall, it is believed that the GeoStat TravTime system yields greater benefits than that of the PC-Travel software. The effects of postprocessing fatigue are dramatic for large projects and have the potential to impart significant error into data sets without warning. With many of the other core error sources corrected, the validity of the data that is recorded is expected to be greater than that of the current system. The GeoStat system hardware can be seen in Figure 3.4.

Figure 3.2: GeoStat System

3.6 Summary of Chapter 3

In order to develop an effective method for automated data collection, the why, where, when, and how must be established. The University of Delaware's project is focused on capturing travel time during the peak periods with the DOT and MPO jurisdictions during the fall and summer seasons. This project also focuses on most of the major collectors, arterials, and freeways servicing the major population centers and summer beach resort areas.

The manner in which the project's data is preprocessed, collected, and postprocessed has a number of shortcomings ranging from control point ambiguity to data processor fatigue. A new method for data collection will need to find a remedy to these points for improvement and meet the needs of the DOT and MPO to be considered a viable solution.

Overall, the Garmin GPS receiver and GeoStats TravTime processing software are able to resolve the greatest number of points for improvement. While some minor issues remain unresolved and other potential concerns exist, it is believed that this new system's benefits outweigh its detriments.

Chapter 4

EXPERIMENTAL PROCEDURES

Prior to the collection and comparison of the experiment's data, experimental design details must be prepared. This preparation includes instrumentation calibration and a description of the experimental data collection procedure.

4.1 Instrumentation Calibration

The instruments that would be used in the experiment included two stopwatches, the current Trimble GPS unit and corresponding laptop, and the Garmin GPS unit and GeoStats GeoLogger. Each of these pieces of equipment were calibrated if possible to ensure that each were operating at the highest possible level of accuracy.

Two RadioShack LCD Multifunction Stopwatches were used for the manual data collection portion of the experiment. The enclosed literature made no reference to any need for stopwatch calibration to ensure accuracy. The manufacturer stated that the stopwatches were accurate to $1/100^{th}$ of a second (19). Because travel time and delay studies are never measured to the $1/10^{th}$ or $1/100^{th}$ of a second accuracy level, it was decided that the manufacturer's calibration of the units would be sufficient. Each unit was assigned to collect either travel time or delay time for the duration of the study.

The Trimble GPS unit was used in the same manner previously described. The literature made no reference to any need for GPS calibration (20). According to literature on the composition of GPS signal data, however, accurate position data can only be determined if the almanac and emphemeris data are up-to-date (21). In the event that the GPS receiver has gone unused for several hours, all almanac and emphemeris data may need to be updated. This process can take up to 12.5 minutes. Therefore the GPS receiver was activated at least 12.5 minutes prior to the beginning of each day's data collection. The softwares used in the data collection process were prepared according to the procedure previously outlined. No additional preparation or calibration was performed manually.

The Garmin GPS unit and GeoLogger were used in the same manner previously described. The user guide accompanying the equipment outlined a list of tasks that should be performed prior to using the equipment in the field (22). First, rules to control the logging functionality of the data logger were established using the unit's download utility software. Logging rules included:

- Speed Filter – this rule would save only speeds above 1.15mph.
- Save Speed – this rule would record a speed for each recorded GPS point.
- Save Altitude – this rule would record altitude for each recorded GPS point.
- Time Filter – this rule would log GPS points less frequently than every one second.

Of these four rules, only the "save speed" rule was activated for delay time counting purposes. Second, the GPS receiver would need to be initialized. Upon first receiving the equipment, the unit must be allowed to obtain a local signal lock before it is used for data collection. To do this, the equipment was set up outdoors in an area with a clear sky view. The unit was then turned on and allowed to sit stationary logging data for approximately 10 minutes. It was noted that this process would only need to be repeated any time the units are transported more than 150 miles while inactive. For preventative measures, the same 12.5 minute almanac and emphemeris data update time was provided prior to each day's data collection.

4.2 Experimental Data Collection Procedure

In order to test the three travel time and delay data collection methods against each other, a number of experiment features and variables were outlined to reduce the potential for biases and errors. Of the core pieces of information needed, only travel time and delay would be collected in the field by each of the three methods independently. The total distance of each segment was supplied by the "Get Directions" feature of Google Maps (23).

First, the location of the data collection test runs was chosen. The route chosen was SR 2, Kirkwood Highway, a 4-lane major arterial serving as a main artery between Wilmington, DE and Newark, DE. The route was studied between its intersections with SR 273 (Main St) and SR 7 (Limestone Rd) and subdivided into four segments. Each route was subdivided into segments based on the separations chosen by DelDOT's Planning Division. The control points and unique characteristics from each segment have been outlined in the Table 4.1. A map of the route layout is depicted in Figure 4.1 (23).

Table 4.1: State Route 2 (Kirkwood Hwy) Segments

Segment	Eastbound	Westbound	Unique Characteristics
1	SR 273 to SR 72	SR 72 to SR 273	Originates in city center. Travels through low-speed residential.
2	SR 72 to Polly Drummond Hill Rd	Polly Drummond Hill Rd to SR 72	Covers short distance surrounded by strip malls.
3	Polly Drummond Hill Rd to Meadowood Dr	Meadowood Dr to Polly Drummond Hill Rd	Several traffic lights through mixed land uses.
4	Meadowood Dr to SR 7	SR 7 to Meadowood Dr	Several traffic lights and additional lane in each direction.

Figure 4.1: Experiment Study Area

The experimental data was collected on weekdays during off-peak hours. It has already been established that peak hours extend from 7AM – 9AM and from 4PM – 6PM so the range of hours selected for off-peak hour study was 10AM – 3PM. Data was collected over several days in the months of October and November of 2009.

All three data collection methods were used simultaneously using one vehicle. A team of data collectors was assembled, all with the basic knowledge and experience needed to collect travel time and delay data using all three methods. On any given day, three members of the team were selected to perform data collection runs. The first person was responsible for driving the vehicle in the same manner as the average driver on the road and operating one stopwatch used for delay time measurements. The second person was responsible for operating the other stopwatch used for travel time measurements. The third person was responsible for operating the Trimble GPS unit and corresponding laptop while logging control point and delay features. As the GeoLogger does not require human interaction to complete its tasks, the second data collector was also responsible for periodically verifying that the data logger's LED continued to display the desired sequence of pulses thereby confirming that it was operating properly. While in the field, the three individuals rotated responsibilities at the conclusion of each run to reduce the likelihood of imparting a single person's data collection or driving habits onto the data.

4.3 Summary of Chapter 4

In order to test the accuracy and measure the automation of the GeoStats system, a data collection procedure was developed to compare the manual method, the Trimble GPS method, and the GeoStats GPS method. Three different methods of data collection operated under identical circumstances can then be compared against each other.

The equipment of each method was calibrated according to the manufacturer specifications. Travel time and delay data was then preprocessed, collected, and postprocessed simultaneously for off-peak traffic conditions along SR 2 in Delaware. The resulting data was later used for statistical comparisons to validate or invalidate the accuracy and automation of each data collection method.

Chapter 5

DATA COLLECTION METHOD EVALUATION

It has been established that several of the procedural points for improvement have been resolved thereby accomplishing an increased automation of the travel time data collection. The increased accuracy, however, requires that mathematical analyses be applied to ensure the viability of any new data collection method. The comparison will be conducted in two parts:

- Evaluation of GPS positioning accuracy.
- Evaluation of travel time and delay measurement accuracy.

The first evaluation will focus on the data collection by the Trimble GPS receiver and the Garmin GPS receiver. The positioning accuracy of each GPS unit varies based on a number of factors. Because the two receivers were not created by the same manufacturer, it is important to verify that they are comparable in their abilities to determine their positions precisely and accurately.

The second evaluation will focus on the experimental data of all three methods: manual, Trimble GPS, and GeoStats GPS. Using a number of methods for comparison, their accuracy in determining travel time and delay will be compared. A hypothesis will be developed to make an inference about the method's viability with respect to the two accepted methods for travel time and delay data collection. Statistical analyses of the experimental data will then be used to reach a decision to accept or reject the developed hypothesis.

5.1 GPS Position Accuracy

All measurement devices have subtle yet implicit sources of inaccuracy and GPS devices are no exception. Positioning determination from a GPS unit can never be exactly accurate or precise due to error sources such as atmospheric effects, multipath effects, clock errors, and relativity. Each unit has internal coding that is used to triangulate its global position. Being placed on the roof of the same vehicle with no more than 3 feet of separation, theoretically two GPS units would be expected to yield nearly identical positioning outputs. However, the internal coding may direct the GPS unit to make certain exclusions or assumptions under circumstances such as high dilution of precision (DOP). Because this internal coding is proprietary and known only by the manufacturer, the device's outputs must be compared relative to each other. If the units are shown to have comparable accuracies, travel time and delay measurements should theoretically be unaffected by the choice of GPS receiver used. However, if the units vary significantly in their accuracies, the travel time and delay data may also exhibit this same inaccuracy due simply to the GPS triangulation methods.

To visually and numerically compare the global position calculated by the GPS receivers, each unit's data sets were postprocessed and formatted for consistency between files. The key pieces of information contained in each file include the latitude, longitude, time stamp, and velocity as recorded on a second-by-second basis by each respective

GPS unit. An additional column was also added to each file to calculate the acceleration of the vehicle over each second. These files were then paired based on the trip number they recorded, therefore, the Trimble GPS file and the GeoStat GPS file of trip number #1 would be paired and so on for trips #2, #3, etc. Each pair of files was imported into a GIS environment and visually overlaid with a shape file containing the roadway network for the state of Delaware.

Initially a simple visual inspection of the GIS map was performed to determine if a notable variation between the GPS unit outputs was apparent. Overall it was found that much of the GPS positioning data did not vary significantly over the entirety of each run, however, in some instances along each run, the precision between units appeared to differ somewhat (Figure 5.1). A GIS tool was used to compute the distance between GPS features with corresponding time stamps (24). The resulting distances would measure the offsets between the positioning readings of both GPS units. From this analysis, the largest offset experienced was approximately 26 feet. Upon further inspection, it could be seen that the locations along the route with the largest offset appeared to be clustered together. Each offset distance was then compared with the velocity and acceleration of the vehicle at each second. While no direct correlation could be found between higher offsets and higher or lower speeds, positive accelerations seem to be related to increased offset distances. This correlation shows that positioning inaccuracy is most likely to occur following a stop at a red traffic signal or stop sign. Because most control points are located at stop signs and traffic signals that may require the vehicle to stop, travel times have the potential to be overestimated or underestimated due to this observed offset between GPS units.

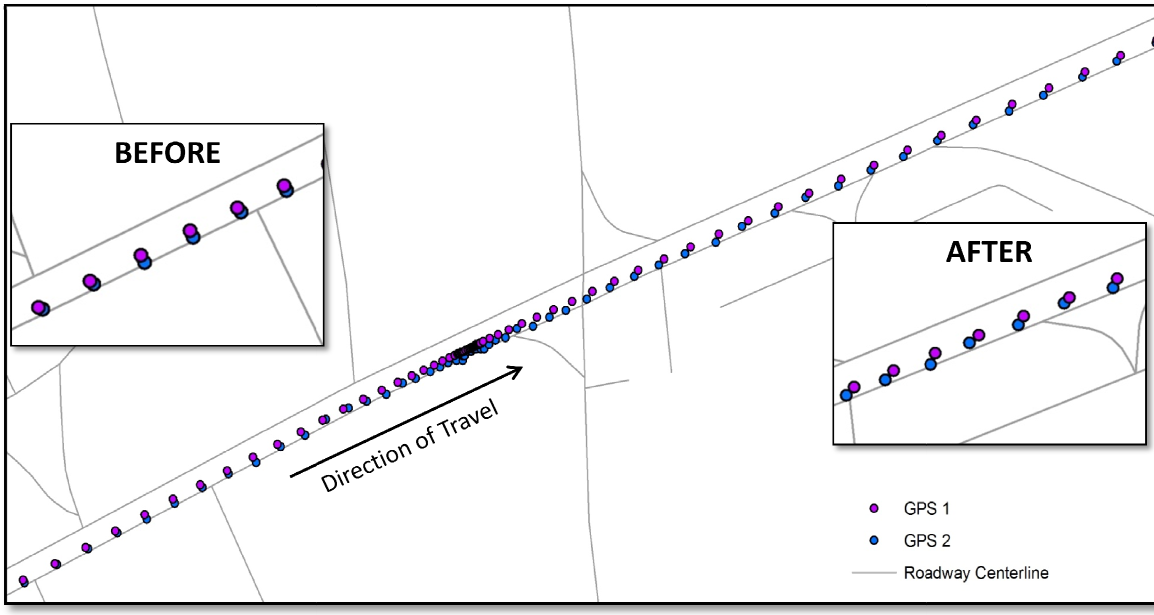

Figure 5.1: GPS Positioning Comparison

To determine if these larger offsets could impose significant travel time inaccuracy, acceptable bounds for this type of error must be determined. The current DelDOT project contains segments with a wide range of lengths, but the most restrictive will be the shortest of these segments being traversed at the highest speed. The shortest segment currently studied is approximately 820 feet in length with a speed limit of 35 mph. Assuming a speed of 35 mph and an underestimation and overestimation of 26 feet at each end of the segment, the travel time ranges from 15.48 to 16.49 seconds. This represents a 3% error which is within the current 5% error bounds observed by the project outline.

Based on this analysis, it can be assumed that the new Garmin GPS unit is acceptably accurate with respect to the current Trimble GPS unit. Therefore, any dramatic difference between travel time and delay readings must be attributed to the data collection procedures rather than the GPS unit triangulation.

5.2 Travel Time and Delay Accuracy

Following the postprocessing of the collected data, statistical tests must be applied to determine whether the new data collection method is comparable in accuracy to the two methods already employed for travel time and delay studies. Determining which statistical tests to apply depends on the characteristics of the data being considered. Each statistical test is based on a set of assumptions about randomness, distribution, independence, etc. In the event that a data set does not meet all of the assumption criteria, it is best to apply several different statistical tests. For analysis of the travel time and delay data, this approach of using a number of tests will be applied to achieve a clearer picture of each data collection method's relationship among the others.

Initially, a common hypothesis is developed to which each statistical test will be applied. The data will then to analyzed using three methods:

1. Analysis of Means and Variances
2. Wilcoxon Signed Rank Test
3. Correlation Analysis

5.2.1 Hypothesis Testing

A statistical hypothesis is a claim about the value of a population characteristic (25). The null hypothesis (H_0) represents the prior belief, or the claim initially assumed to be true. The contridictory claim is known as the alternative hypothesis (H_a). The null hypothesis is understood to be true unless the sample evidence suggests that H_0 is false, in which case H_0 is rejected in favor of H_a (25). Hypothesis testing is used to reach a decision to reject H_0 or fail to reject H_0. To test the mean of a sample, there are three basic hypothesis tests available:

Table 5.1: Hypothesis Tests

Test 1	Test 2	Test 3
H_0: $\mu \geq \mu_0$	H_0: $\mu \leq \mu_0$	H_0: $\mu = \mu_0$
H_a: $\mu < \mu_0$	H_a: $\mu > \mu_0$	H_a: $\mu \neq \mu_0$

Tests 1 and 2 represent one-tailed hypothesis tests essentially making a decision about which value is higher or lower than the other. Test 3, however, represents a two-tailed hypothesis test in which neither value is decidedly higher or lower, but simply that the values are the same or different. Because of the implicit errors present in data measurement, the absolute truth with regards to travel time and delay can never be known. Without an absolute truth to compare all other measures to, a decision about which data collection method is superior can not be made. In this case, the two-tailed hypothesis will be adopted to show whether the three data collection methods are equal or different. Therefore, the hypothesis to be tested is as follows:

H_0: the methods are the same

H_a: the methods are different

5.2.2 Analysis of Means and Variances

Two samples of measurements, even when taken from the same population, are unlikely to have exactly the same mean. By testing for significant differences between means of two samples of measurements, it can be determined whether these differences are due to chance or if they are statistically significant. To perform such a comparison, the numerical differences in the means and the variability of the measurements in the two samples are evaluated. The variability of the measurements is characterized as the standard deviation of the difference of the means (ŝ) and can be calculated as (26):

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

s1, n1 = standard deviation and number of observations in sample 1

s2, n2 = standard deviation and number of observations in sample 2

Over a normal distribution of the difference in means, ŝ, 2ŝ, and 3ŝ represent the 68.26, 95.46, and 99.73 percent of cases respectively. If the numerical difference in means falls outside of ±3ŝ, that value would be considered highly suspect and unlikely to be due to chance alone (26). Therefore, for values that fall between ±ŝ, H_0 will be accepted.

After applying the formulas to the collected travel time and delay data, the resulting comparisons indicate that H_0 is accepted in every case (Table 5.2 – Table 5.5). Therefore, with regards to the sample means of each data collection method, all three methods generate comparable values and are essentially the same. These results are also displayed in Figures 5.2 – 5.5.

In the same fashion, two samples of measurements, even when taken from the same population, are unlikely to have exactly the same variance. For this comparison, the F test is used to compare the ratio of the two sample variances with the values taken from the F distribution at the 0.05 level [28]. A value of F close to 1 provides evidence that the underlying population variances are equal. If $F < 1$, F_{crit} gives the critical value less than 1 for $\alpha=0.05$. If $F > 1$, F_{crit} gives the critical value greater than 1 for $\alpha=0.05$ (27). If the value of F lies between 1 and F_{crit}, H_0 will be accepted.

After applying the F-test to the collected travel time and delay data, the resulting comparisons indicate that H_0 is accepted in every case (Table 5.6 – Table 5.9). Therefore, with regards to the sample variances of each data collection method, all three methods generate comparable values and are essentially the same.

Table 5.2: Analysis of Means for Segment 1

	Comparison	Δμ	ŝ	2ŝ	3ŝ	H_0
Travel Time Eastbound	Manual_Trimble	0.15	9.77	19.53	29.30	accept
	Trimble_GeoStats	7.77	9.29	18.58	27.87	accept
	Manual_GeoStats	7.62	9.22	18.44	27.66	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Travel Time Westbound	Manual_Trimble	1.44	7.55	15.10	22.65	accept
	Trimble_GeoStats	1.79	7.52	15.03	22.55	accept
	Manual_GeoStats	3.23	7.53	15.07	22.60	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Delay Time Eastbound	Manual_Trimble	1.36	8.41	16.82	25.23	accept
	Trimble_GeoStats	5.58	7.76	15.51	23.27	accept
	Manual_GeoStats	6.94	7.93	15.87	23.80	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Delay Time Westbound	Manual_Trimble	0.56	6.44	12.88	19.32	accept
	Trimble_GeoStats	0.10	6.46	12.92	19.38	accept
	Manual_GeoStats	0.45	6.46	12.92	19.38	accept

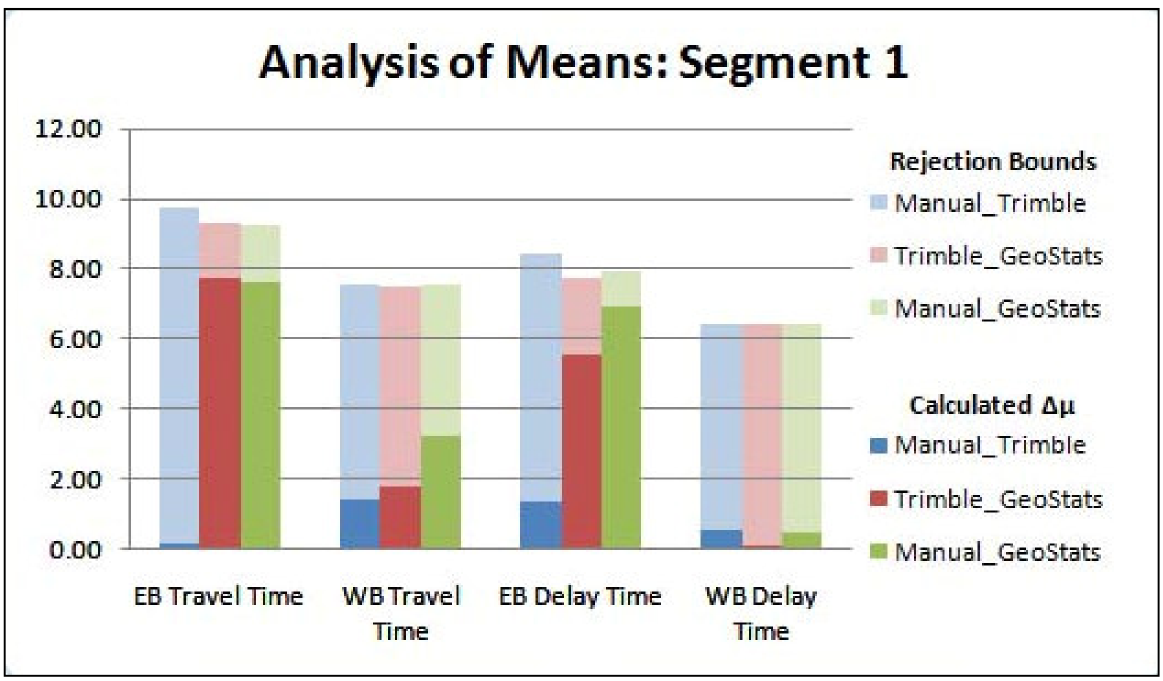

Figure 5.2: Analysis of Means for Segment 1

Table 5.3: Analysis of Means for Segment 2

	Comparison	Δμ	ŝ	2ŝ	3ŝ	H_0
Travel Time Eastbound	Manual_Trimble	0.11	9.22	18.44	27.66	accept
	Trimble_GeoStats	4.71	9.47	18.93	28.40	accept
	Manual_GeoStats	4.82	9.45	18.91	28.36	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Travel Time Westbound	Manual_Trimble	0.97	6.88	13.76	20.64	accept
	Trimble_GeoStats	0.04	6.91	13.83	20.74	accept
	Manual_GeoStats	1.01	6.95	13.90	20.85	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Delay Time Eastbound	Manual_Trimble	0.29	8.86	17.71	26.57	accept
	Trimble_GeoStats	4.12	9.12	18.23	27.35	accept
	Manual_GeoStats	4.41	9.25	18.49	27.74	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Delay Time Westbound	Manual_Trimble	0.28	4.82	9.64	14.45	accept
	Trimble_GeoStats	0.03	4.67	9.33	14.00	accept
	Manual_GeoStats	0.31	4.82	9.65	14.47	accept

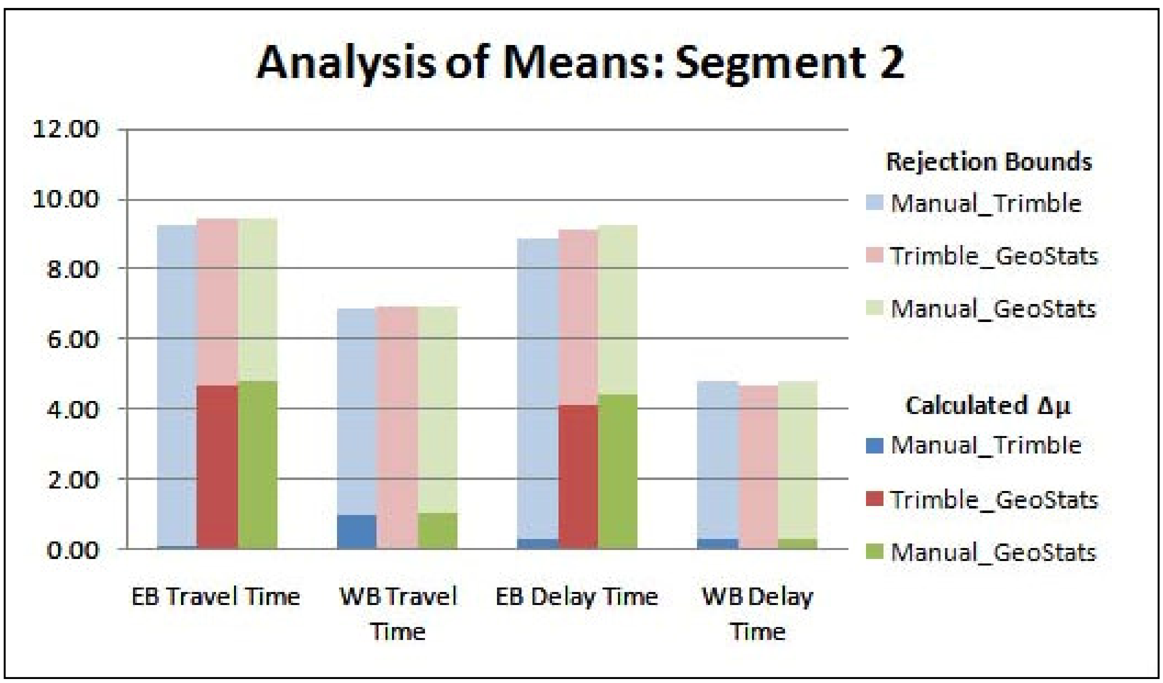

Figure 5.3: Analysis of Means for Segment 2

Table 5.4: Analysis of Means for Segment 3

	Comparison	Δμ	ŝ	2ŝ	3ŝ	H_0
Travel Time Eastbound	Manual_Trimble	3.22	10.19	20.37	30.56	accept
	Trimble_GeoStats	4.93	10.35	20.71	31.06	accept
	Manual_GeoStats	1.71	10.53	21.07	31.60	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Travel Time Westbound	Manual_Trimble	0.04	12.73	25.46	38.19	accept
	Trimble_GeoStats	0.01	12.76	25.51	38.27	accept
	Manual_GeoStats	0.05	12.77	25.55	38.32	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Delay Time Eastbound	Manual_Trimble	4.07	8.04	16.08	24.12	accept
	Trimble_GeoStats	4.30	8.21	16.43	24.64	accept
	Manual_GeoStats	0.23	8.69	17.38	26.07	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Delay Time Westbound	Manual_Trimble	5.80	9.09	18.18	27.28	accept
	Trimble_GeoStats	4.76	9.09	18.17	27.26	accept
	Manual_GeoStats	1.04	10.22	20.44	30.66	accept

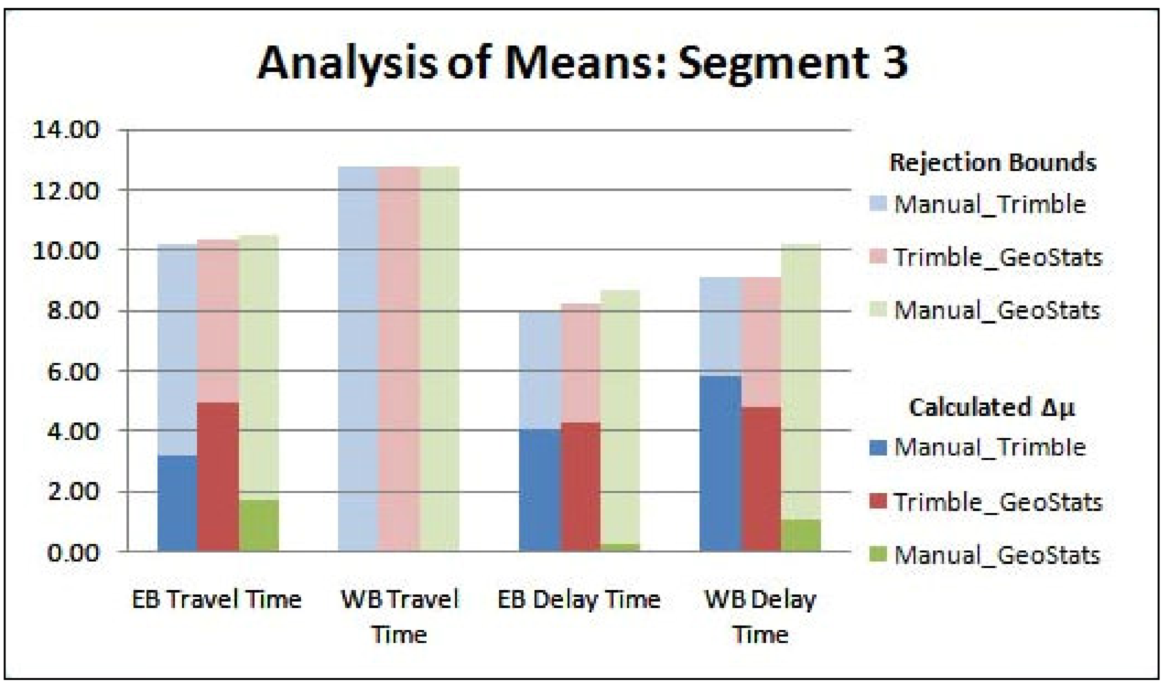

Figure 5.4: Analysis of Means for Segment 3

Table 5.5: Analysis of Means for Segment 4

	Comparison	Δμ	ŝ	2ŝ	3ŝ	H_0
Travel Time Eastbound	Manual_Trimble	1.53	16.03	32.06	48.09	accept
	Trimble_GeoStats	3.04	16.66	33.32	49.98	accept
	Manual_GeoStats	1.51	16.37	32.75	49.12	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Travel Time Westbound	Manual_Trimble	0.41	8.71	17.41	26.12	accept
	Trimble_GeoStats	0.07	8.72	17.43	26.15	accept
	Manual_GeoStats	0.33	8.64	17.27	25.91	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Delay Time Eastbound	Manual_Trimble	3.85	14.84	29.68	44.52	accept
	Trimble_GeoStats	0.92	14.94	29.87	44.81	accept
	Manual_GeoStats	4.77	15.00	29.99	44.99	accept
	Comparison	**Δμ**	**ŝ**	**2ŝ**	**3ŝ**	**H_0**
Delay Time Westbound	Manual_Trimble	0.96	6.50	12.99	19.49	accept
	Trimble_GeoStats	0.15	6.36	12.71	19.07	accept
	Manual_GeoStats	0.81	6.50	13.01	19.51	accept

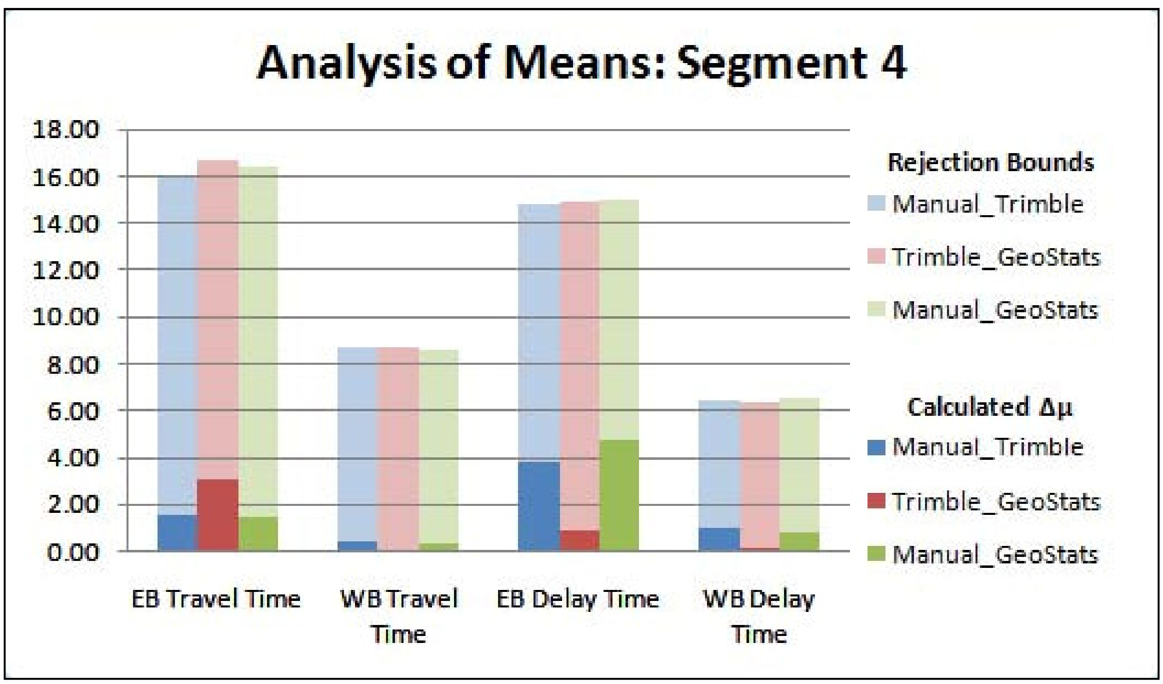

Figure 5.5: Analysis of Means for Segment 4

Table 5.6: Analysis of Variances for Segment 1

	Comparison	F	F_{crit}	H_0
Travel Time Eastbound	Manual_Trimble	0.97	0.52	accept
	Trimble_GeoStats	1.49	2.05	accept
	Manual_GeoStats	1.45	2.05	accept
	Comparison	**F**	F_{crit}	H_0
Travel Time Westbound	Manual_Trimble	0.97	0.51	accept
	Trimble_GeoStats	1.01	1.93	accept
	Manual_GeoStats	0.98	0.51	accept
	Comparison	**F**	F_{crit}	H_0
Delay Time Eastbound	Manual_Trimble	1.04	1.94	accept
	Trimble_GeoStats	1.52	2.01	accept
	Manual_GeoStats	1.59	2.02	accept
	Comparison	**F**	F_{crit}	H_0
Delay Time Westbound	Manual_Trimble	1.00	0.52	accept
	Trimble_GeoStats	0.99	0.52	accept
	Manual_GeoStats	0.99	0.52	accept

Table 5.7: Analysis of Variances for Segment 2

	Comparison	F	F_{crit}	H_0
Travel Time Eastbound	Manual_Trimble	0.99	0.52	accept
	Trimble_GeoStats	1.06	2.01	accept
	Manual_GeoStats	1.06	2.01	accept
	Comparison	**F**	F_{crit}	H_0
Travel Time Westbound	Manual_Trimble	0.98	0.51	accept
	Trimble_GeoStats	0.96	0.52	accept
	Manual_GeoStats	0.94	0.51	accept
	Comparison	**F**	F_{crit}	H_0
Delay Time Eastbound	Manual_Trimble	1.02	1.94	accept
	Trimble_GeoStats	0.99	0.51	accept
	Manual_GeoStats	1.01	2.02	accept
	Comparison	**F**	F_{crit}	H_0
Delay Time Westbound	Manual_Trimble	1.09	1.94	accept
	Trimble_GeoStats	1.00	0.52	accept
	Manual_GeoStats	1.09	1.94	accept

Table 5.8: Analysis of Variances for Segment 3

	Comparison	F	F_{crit}	H_0
Travel Time Eastbound	Manual_Trimble	1.12	1.95	accept
	Trimble_GeoStats	0.91	0.51	accept
	Manual_GeoStats	1.01	1.97	accept
	Comparison	**F**	F_{crit}	H_0
Travel Time Westbound	Manual_Trimble	1.01	1.93	accept
	Trimble_GeoStats	0.99	0.52	accept
	Manual_GeoStats	0.99	0.52	accept
	Comparison	**F**	F_{crit}	H_0
Delay Time Eastbound	Manual_Trimble	1.33	1.95	accept
	Trimble_GeoStats	0.75	0.51	accept
	Manual_GeoStats	1.00	1.97	accept
	Comparison	**F**	F_{crit}	H_0
Delay Time Westbound	Manual_Trimble	1.79	1.95	accept
	Trimble_GeoStats	0.56	0.51	accept
	Manual_GeoStats	1.00	1.93	accept

Table 5.9: Analysis of Variances for Segment 4

	Comparison	F	F_{crit}	H_0
Travel Time Eastbound	Manual_Trimble	0.96	0.52	accept
	Trimble_GeoStats	0.96	0.51	accept
	Manual_GeoStats	0.93	0.51	accept
	Comparison	**F**	F_{crit}	H_0
Travel Time Westbound	Manual_Trimble	0.96	0.52	accept
	Trimble_GeoStats	1.03	1.93	accept
	Manual_GeoStats	1.00	0.52	accept
	Comparison	**F**	F_{crit}	H_0
Delay Time Eastbound	Manual_Trimble	1.06	1.95	accept
	Trimble_GeoStats	1.00	0.51	accept
	Manual_GeoStats	1.05	1.97	accept
	Comparison	**F**	F_{crit}	H_0
Delay Time Westbound	Manual_Trimble	1.09	1.93	accept
	Trimble_GeoStats	0.99	0.52	accept
	Manual_GeoStats	1.09	1.93	accept

5.2.3 Wilcoxon Signed Rank Test

Nonparametric or distribution-free procedures are used in cases when the distributional assumption of normality is invalid. Past studies of travel time and delay data have determined that the data does not follow a normal distribution because of the variability in the frequency and duration of signalized intersection interruptions (6) (28). Based on the assumption of nonnormal data, the nonparametric Wilcoxon Signed-Rank Test will be used. This test determines the magnitude of departures from the hypothetical median among the sample population (29).

The measured travel times and delay times are first paired for direct comparison. If these data collection methods were all identical, their differences would always reach a median value of zero. Therefore, from each pair, a difference is calculated and applied using a two-tailed approach. These absolute values of these differences are arranged in order of magnitude and assigned ranks in ascending order. Finally, the ranks of the nonnegative differences are summed which yield the Wilcoxon W value. W values that are relatively high or relatively low suggest a large number of values are shifted above or below the hypothetical median. Additionally, each comparison generates a P-value which represents the exact probability of obtaining a value of $|t|$ equal to or greater than that observed when H_0 is true (29) (30). At the $\alpha = 0.05$ level, if the P-value ≥ 0.05, H_0 will be accepted.

The results of the Wilcoxon Signed Rank Test (Table 5.10 – Table 5.13) show that in every case, the manual method and Trimble method are considered comparable with regards to travel time measurements. Additionally, in every case, the Trimble method and GeoStats method are considered comparable with regards to delay time measurements. These results are expected based on the manner in which the data is collected. The manual method involves human intervention for both travel time and delay data. The Trimble method involves human intervention for travel time data, but delay data is automated. The GeoStats method is automated for both travel time and delay data.

Table 5.10: Wilcoxon Signed Rank Test for Segment 1

	Comparison	Wilcoxon W	P	Est Median	H_0
Travel Time Eastbound	Manual_Trimble	53.0	0.453	0.00	accept
	Trimble_GeoStats	227.0	0.007	0.80	reject
	Manual_GeoStats	221.5	0.002	0.60	reject
	Comparison	**Wilcoxon W**	**P**	**Est Median**	H_0
Travel Time Westbound	Manual_Trimble	69.0	0.315	0.00	accept
	Trimble_GeoStats	366.5	0.000	1.90	reject
	Manual_GeoStats	351.0	0.000	2.00	reject
	Comparison	**Wilcoxon W**	**P**	**Est Median**	H_0
Delay Time Eastbound	Manual_Trimble	64.5	0.050	0.50	accept
	Trimble_GeoStats	45.0	0.660	0.00	accept
	Manual_GeoStats	76.5	0.363	0.10	accept
	Comparison	**Wilcoxon W**	**P**	**Est Median**	H_0
Delay Time Westbound	Manual_Trimble	165.5	0.025	1.00	reject
	Trimble_GeoStats	60.0	0.698	0.00	accept
	Manual_GeoStats	185.0	0.060	0.75	accept

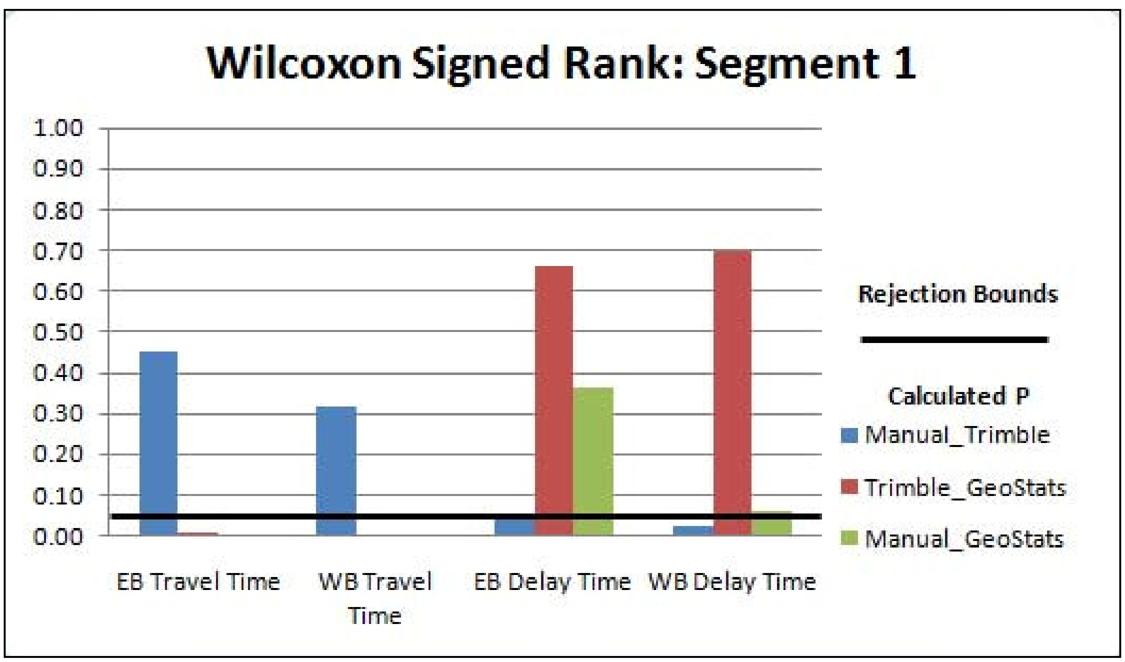

Figure 5.6: Wilcoxon Signed Rank Test for Segment 1

Table 5.11: Wilcoxon Signed Rank Test for Segment 2

	Comparison	Wilcoxon W	P	Est Median	H_0
Travel Time Eastbound	Manual_Trimble	30.0	0.505	0.00	accept
	Trimble_GeoStats	116.5	0.523	-0.10	accept
	Manual_GeoStats	105.5	0.330	-0.20	accept
	Comparison	**Wilcoxon W**	**P**	**Est Median**	H_0
Travel Time Westbound	Manual_Trimble	24.0	0.255	0.00	accept
	Trimble_GeoStats	146.5	0.932	0.00	accept
	Manual_GeoStats	125.5	0.493	-0.10	accept
	Comparison	**Wilcoxon W**	**P**	**Est Median**	H_0
Delay Time Eastbound	Manual_Trimble	91.0	0.017	0.50	reject
	Trimble_GeoStats	80.5	0.845	0.00	accept
	Manual_GeoStats	164.0	0.029	0.70	reject
	Comparison	**Wilcoxon W**	**P**	**Est Median**	H_0
Delay Time Westbound	Manual_Trimble	91.0	0.002	0.50	reject
	Trimble_GeoStats	51.0	0.727	0.00	accept
	Manual_GeoStats	120.0	0.001	0.90	reject

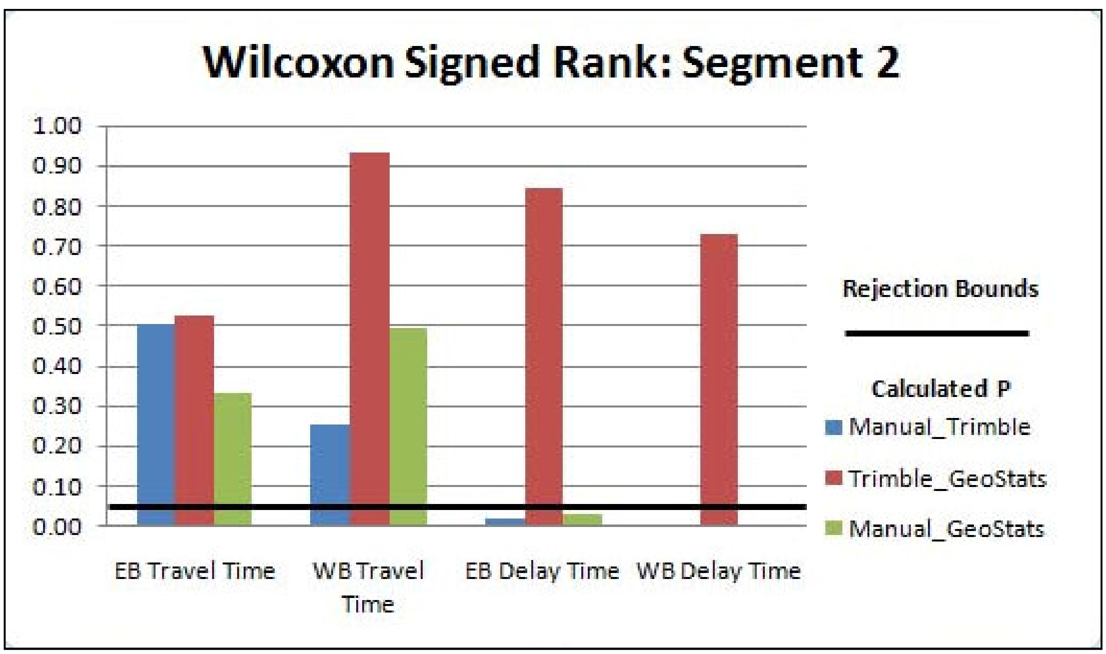

Figure 5.7: Wilcoxon Signed Rank Test for Segment 2

Table 5.12: Wilcoxon Signed Rank Test for Segment 3

	Comparison	Wilcoxon W	P	Est Median	H_0
Travel Time Eastbound	Manual_Trimble	49.5	0.155	0.00	accept
	Trimble_GeoStats	170.5	0.015	0.30	reject
	Manual_GeoStats	196.0	0.001	0.50	reject
	Comparison	**Wilcoxon W**	**P**	**Est Median**	**H_0**
Travel Time Westbound	Manual_Trimble	42.0	0.834	0.00	accept
	Trimble_GeoStats	154.0	0.830	0.00	accept
	Manual_GeoStats	125.0	0.704	0.00	accept
	Comparison	**Wilcoxon W**	**P**	**Est Median**	**H_0**
Delay Time Eastbound	Manual_Trimble	136.0	0.000	1.00	reject
	Trimble_GeoStats	83.0	0.644	-0.05	accept
	Manual_GeoStats	136.0	0.000	1.10	reject
	Comparison	**Wilcoxon W**	**P**	**Est Median**	**H_0**
Delay Time Westbound	Manual_Trimble	153.0	0.000	1.00	reject
	Trimble_GeoStats	142.0	0.626	0.00	accept
	Manual_GeoStats	302.0	0.000	1.00	reject

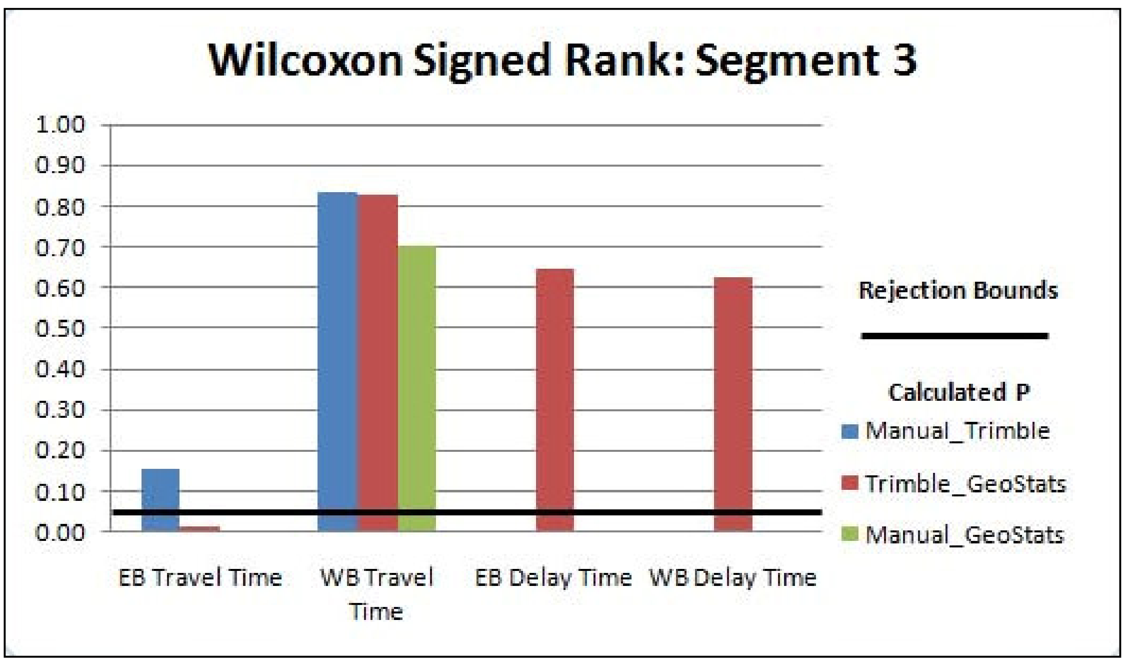

Figure 5.8: Wilcoxon Signed Rank Test for Segment 3

Table 5.13: Wilcoxon Signed Rank Test for Segment 4

	Comparison	Wilcoxon W	P	Est Median	H_0
Travel Time Eastbound	Manual_Trimble	24.0	0.255	0.00	accept
	Trimble_GeoStats	268.5	0.001	1.10	reject
	Manual_GeoStats	257.0	0.002	1.00	reject
	Comparison	**Wilcoxon W**	**P**	**Est Median**	**H_0**
Travel Time Westbound	Manual_Trimble	50.0	0.589	0.00	accept
	Trimble_GeoStats	278.0	0.010	0.60	reject
	Manual_GeoStats	293.5	0.012	0.30	reject
	Comparison	**Wilcoxon W**	**P**	**Est Median**	**H_0**
Delay Time Eastbound	Manual_Trimble	193.5	0.007	1.00	reject
	Trimble_GeoStats	100.0	0.867	0.00	accept
	Manual_GeoStats	204.5	0.012	1.30	reject
	Comparison	**Wilcoxon W**	**P**	**Est Median**	**H_0**
Delay Time Westbound	Manual_Trimble	146.5	0.001	0.50	reject
	Trimble_GeoStats	60.5	0.286	-0.10	accept
	Manual_GeoStats	158.5	0.002	0.60	reject

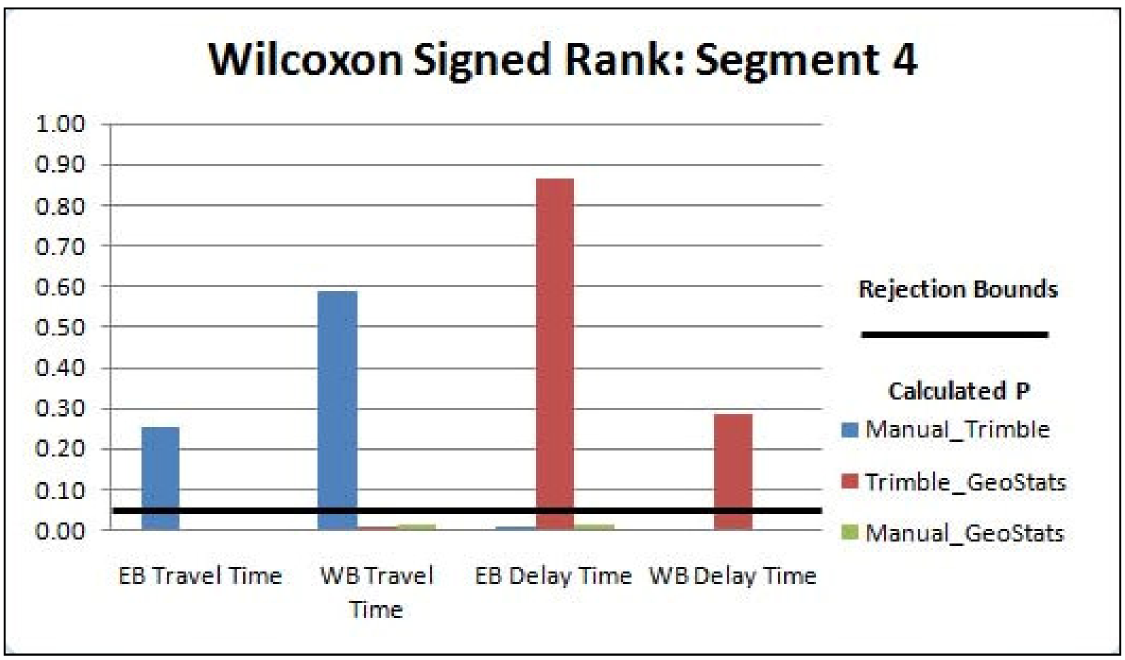

Figure 5.9: Wilcoxon Signed Rank Test for Segment 4

5.2.4 Correlation Analysis

The correlation coefficient is a measure of the extent to which two measurement variables are related to each other (27). The Pearson Product Moment Correlation Coefficient estimates the degree of linear association yielding a Pearson correlation coefficient, r. Values of r close to ±1 represent strong positive or negative correlations, however, values of r close to zero represent an independence between the two variables (29). The Pearson correlation coefficient is determined by the following equation:

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2}}$$

The results of the Pearson correlation coefficient (Table 5.14 – Table 5.17) show a strong association between the three data collection methods for both travel time and delay time measurements. This is evident by the fact that most r-values are 0.99 and up, with the lowest r-value being 0.9222.

In a nonparametric context, the assumption of normality is no longer required. As stated previously, past studies of travel time and delay data have determined that the data does not follow a normal distribution, therefore, a nonparametric correlation will be applied as well. The Spearman Rank Correlation Coefficient is computationally equivalent to the Pearson coefficient calculated for ranks (29). The Spearman correlation coefficient is determined by the following equation:

$$r_s = 1 - \frac{6 \sum_i (r_i - s_i)^2}{n(n^2 - 1)}$$

The results of the Spearman correlation coefficient (Table 5.18 – 5.21) also show a strong association between the data collection methods. Again, most r_s-values are 0.99

and up, with the lowest r_s-value being 0.9430. Therefore, H_0 is accepted as the data sets from each data collection method do not vary significantly from each other.

Table 5.14: Pearson Correlation Analysis for Segment 1

		Eastbound			Westbound		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Travel Time	Manual	1			1		
	Trimble	0.9998	1		0.9994	1	
	GeoStats	0.9820	0.9829	1	0.9996	0.9993	1
		Eastbound			**Westbound**		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Delay Time	Manual	1			1		
	Trimble	0.9986	1		0.9924	1	
	GeoStats	0.9794	0.9777	1	0.9924	0.9995	1

Table 5.15: Pearson Correlation Analysis for Segment 2

		Eastbound			Westbound		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Travel Time	Manual	1			1		
	Trimble	0.9998	1		0.9995	1	
	GeoStats	0.9859	0.9869	1	0.9998	0.9996	1
		Eastbound			**Westbound**		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Delay Time	Manual	1			1		
	Trimble	0.9963	1		0.9979	1	
	GeoStats	0.9838	0.9886	1	0.9983	0.9992	1

Table 5.16: Pearson Correlation Analysis for Segment 3

		Eastbound			Westbound		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Travel Time	Manual	1			1		
	Trimble	0.9997	1		0.9998	1	
	GeoStats	0.9923	0.9908	1	0.9999	0.9999	1
		Eastbound			**Westbound**		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Delay Time	Manual	1			1		
	Trimble	0.9993	1		0.9995	1	
	GeoStats	0.9907	0.9872	1	0.9996	0.9997	1

Table 5.17: Pearson Correlation Analysis for Segment 4

		Eastbound			Westbound		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Travel Time	Manual	1			1		
	Trimble	0.9999	1		0.9951	1	
	GeoStats	0.9972	0.9974	1	0.9998	0.9949	1
		Eastbound			**Westbound**		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Delay Time	Manual	1			1		
	Trimble	0.9986	1		0.9991	1	
	GeoStats	0.9222	0.9969	1	0.9987	0.9996	1

Table 5.18: Spearman Correlation Analysis for Segment 1

		Eastbound			Westbound		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Travel Time	Manual	1			1		
	Trimble	0.9980	1		0.9980	1	
	GeoStats	0.9430	0.9430	1	1.0000	0.9990	1
		Eastbound			**Westbound**		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Delay Time	Manual	1			1		
	Trimble	0.9960	1		0.9840	1	
	GeoStats	0.9800	0.9810	1	0.9830	0.9990	1

Table 5.19: Spearman Correlation Analysis for Segment 2

		Eastbound			Westbound		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Travel Time	Manual	1			1		
	Trimble	0.9990	1		0.9990	1	
	GeoStats	0.9720	0.9760	1	1.0000	0.9990	1
		Eastbound			**Westbound**		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Delay Time	Manual	1			1		
	Trimble	0.9990	1		0.9980	1	
	GeoStats	0.9800	0.9820	1	0.9980	0.9980	1

Table 5.20: Spearman Correlation Analysis for Segment 3

		Eastbound			Westbound		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Travel Time	Manual	1			1		
	Trimble	0.9990	1		1.0000	1	
	GeoStats	0.9970	0.9960	1	0.9990	0.9990	1
		Eastbound			**Westbound**		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Delay Time	Manual	1			1		
	Trimble	0.9940	1		0.9990	1	
	GeoStats	0.9950	0.9860	1	0.9990	0.9990	1

Table 5.21: Spearman Correlation Analysis for Segment 4

		Eastbound			Westbound		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Travel Time	Manual	1			1		
	Trimble	0.9990	1		0.9970	1	
	GeoStats	0.9970	0.9980	1	1.0000	0.9980	1
		Eastbound			**Westbound**		
		Manual	**Trimble**	**GeoStats**	**Manual**	**Trimble**	**GeoStats**
Delay Time	Manual	1			1		
	Trimble	0.9980	1		0.9990	1	
	GeoStats	0.9460	0.9990	1	0.9990	1.0000	1

5.3 Results of Comparison

To test the hypothesis of whether the manual method, the Trimble GPS method, and the GeoStats GPS method are statistically the same or different, the data sets were paired and analyzed using the Analysis of Means, Analysis of Variances, Wilcoxon Signed Rank Test, Pearson Correlation Analysis, and Spearman Correlation Analysis. All but the Wilcoxon Signed Rank Test suggested that the three data collection methods perform equally well when measuring both travel time and delay time. The summarized results can be found in Table 5.22 – Table 5.23.

The Wilcoxon Signed Rank Test appears to be the most restrictive in terms of classifying the data collection methods similarly. At a confidence level of 95 percent, H_0 was accepted for the following number of data pairs:

- Travel time – 14 out of 24 pairs
- Delay time – 11 out of 24 pairs

As only about half of the data pairs accepted H_0, this may not be enough to fail to reject the hypothesis that all methods perform equally. As stipulated previously, it cannot be known which data collection method is superior, however, inferences can be made in an attempt to explain the results.

From the Wilcoxon Signed Rank Test, a strong relationship can be found between the manual method and the Trimble GPS method with regards to travel time measurement. Additionally, a strong relationship can be found between the Trimble GPS method and the GeoStats GPS method with regards to delay time measurement. Based on the manner in which data is collected through each method, it is expected that these relationships exist. The manual method involves human intervention for both travel time and delay data. The Trimble method involves human intervention for travel time data, but delay data is automated. The GeoStats method is automated for both travel time and delay data. The commonality between the Wilcoxon relationships and the manner of measurement coincide perfectly. From this it may be inferred that the manual method is inferior to the GPS methods with regards to delay measurement because of its dependence on human precision and accuracy. By the same argument it may be inferred that the manual and Trimble GPS methods are inferior with regards to travel time measurement, also because of their dependence on human precision and accuracy. Overall, the results of all five tests suggest that all three data collection methods perform equally well.

Table 5.22: Summary of Statistical Test for Travel Time Measurement

Test	Dir	Segment	Manual_Trimb	Trimble_GeoSta	Manual_GeoSta
Analysis of Means	EB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
	WB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
Analysis of Variances	EB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
	WB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
Wilcoxon Signed Rank	EB	1	✓	-	-
		2	✓	✓	✓
		3	✓	-	-
		4	✓	-	-
	WB	1	✓	-	-
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	-	-
Pearson Correlation	EB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
	WB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
Spearman Correlation	EB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
	WB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓

Table 5.23: Summary of Statistical Test for Delay Time Measurement

Test	Dir	Segment	Manual_Trimble	Trimble_GeoStats	Manual_GeoStats
Analysis of Means	EB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
	WB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
Analysis of Variances	EB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
	WB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
Wilcoxon Signed Rank	EB	1	✓	✓	✓
		2	-	✓	-
		3	-	✓	-
		4	-	✓	-
	WB	1	-	✓	✓
		2	-	✓	-
		3	-	✓	-
		4	-	✓	-
Pearson Correlation	EB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
	WB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
Spearman Correlation	EB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓
	WB	1	✓	✓	✓
		2	✓	✓	✓
		3	✓	✓	✓
		4	✓	✓	✓

5.4 Summary of Chapter 5

By establishing the resolution of most points for improvement from Chapter 3, an increase in automation has been achieved using the GeoStat software. Evaluation of the accuracy, however, requires mathematical analyses conducted in two parts.

First the GPS units were evaluated to compare their global posititioning outputs to each other. It was found that overall, much of the GPS positioning data did not vary significantly, but in some instances, precision appeared to differ somewhat. Based on the largest offset in positioning precision, the error between units totaled only 3% which is considered acceptable by the project's 5% error bounds. Without knowing the true position at each second along the route, it can only be said that both GPS units are comparable in their positioning abilities.

Second the three methods were evaluated to compare their travel time and delay outputs to each other. Analysis of Means, Analysis of Variances, Wilcoxon Signed Rank Test, and Pearson and Spearman Correlation Analyses were used to test the hypothesis that all three methods perform equally well statistically speaking. All but the Wilcoxon Signed Rank Test definitively supported the hypothesis that each method was statistically comparable.

Chapter 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

This thesis tested and evaluated three methods used for travel time and delay data collection. A 27-run sample set of manual, Trimble GPS, and GeoStats GPS data was collected for evaluation.

With the goal of identifying the most accurate and automated method for data collection, an experimental data collection procedure was applied to gather numerous samples of data. Advancement in automation was determined subjectively by evaluating the available features in each method and considering the opportunities for error to be imparted on the data. This analysis greatly favored the GeoStats GPS method over the rest.

Accuracy, however, was determined objectively using a number of avenues. First, each GPS unit was evaluated for positioning accuracy during data collection conditions. Second, the data samples were statistically analyzed using a combination of parametric and nonparametric statistical tests. Using the Analysis of Means, Analysis of Variances, Wilcoxon Signed Rank Test, Pearson Correlation Analysis, and Spearman Correlation Analysis, overall results showed that all data collection methods perform equally well for both travel time and delay time measurements. The Wilcoxon Signed

Rank Test deviated slightly verifying only that manual and Trimble GPS perform equally well for travel time data, and Trimble GPS and GeoStats GPS perform equally well for delay time data.

6.2 Conclusions

In an effort to test and evaluate the three methods of travel time and delay data collection, this experiment set out to complete the following tasks:

1. Examine each travel time and delay data collection method to determine which provides the greatest benefit to DelDOT and WILMAPCO.
2. Perform a detailed analysis of the possible sources of human error in an attempt to eliminate as many sources of error as possible for the preprocessing, data collection, and postprocessing phases.
3. Consider the specific features, methods, and assumptions adopted for this particular application of data collection will be performed.
4. Determine the optimal method for performing an active test vehicle travel time and delay data collection study with focus placed on automation and accuracy.

Task 1 was completed based on the limited number of processing softwares with travel time and delay applications that have been evaluated in this study. While every attempt was given to consider all alternatives currently available, the development of a specially tailored computer program was not undertaken. It could be expected that a program designed especially for DelDOT and WILMAPCO's needs could yield an even greater benefit by eliminating more sources of error.

Task 2 and 3 were completed by conducting an in-depth consideration of each step in the process of data collection. This comprehensive consideration was prepared following several years of active data processing. This experience provided an essential view into the details of the project analysis process.

Task 4 was partially completed based on the results of the statistical analyses performed. Without knowing a ground truth value for the GPS position data or the travel time and delay data, these analyses cannot definitively state that one method for data collection is superior to any other. However, the analyses generally showed little difference between data collection methods. Therefore, from an accuracy standpoint, it can be concluded that all methods are suitable for travel time and delay data collection, provided they are practiced with the highest degree of human precision. With the additional benefit of significant automation, the GeoStats GPS method is suggested as it has shown consistent performance with minimal opportunities for human error to be imparted.

6.3 Recommendations

This evaluation involved the consideration of data measured on a signalized arterial during off-peak hours. Additional research could be conducted to investigate the relationships between data collection methods in freeway environments. Additional research could also consider data collection during congestion events. This analysis could compare the effects of different road types and different level of service performance on the variability between data collection methods.

Future evaluations should also consider the task of developing a software or computer program that is specifically tailored to the needs of the DelDOT/WILMAPCO travel time and delay project and to the roadway network that is covered by this project. The potential for other data collection techniques to be used in the future should also be considered. The active test vehicle technique was chosen for its flexibility and minimal infrastructure requirements, however, on major freeways there will always be a need for travel time data and an infrastructure investment may be more beneficial for long term goals.

A. APPENDIX A

TRAVEL TIME MEASUREMENTS

Table A.1: Eastbound and Westbound Travel Time in seconds for Segment 1

Sample	Eastbound			Westbound		
	Manual	Trimble	GeoStats	Manual	Trimble	GeoStats
1	107	107	107.4	140	139	136.8
2	184	184	183.6	144	144	141.6
3	110	110	109.8	155	156	153
4	155	155	154.8	164	163	162
5	126	126	*	166	166	163.2
6	138	139	138	130	131	127.8
7	180	180	*	194	194	193.2
8	133	134	131.4	121	122	119.4
9	144	145	*	113	111	112.8
10	183	184	182.4	122	121	120
11	125	126	125.4	136	136	133.8
12	121	122	119.4	153	153	150.6
13	151	152	150	102	102	100.2
14	141	141	139.8	186	186	184.2
15	124	123	124.2	154	152	151.2
16	253	254	*	157	155	153
17	131	130	103.8	135	135	133.2
18	107	106	106.2	135	135	133.2
19	108	108	106.8	193	193	191.4
20	100	98	100.2	148	148	146.4
21	190	192	189.6	152	151	150
22	120	119	118.8	208	209	205.8
23	185	186	184.8	191	192	190.2
24	137	137	137.4	119	120	117.6
25	106	106	104.4	162	161	160.8
26	107	106	105.6	*	118	115.8
27	163	163	162.6	171	171	168.6

* = Data invalid due to human or computer error.

Table A.2: Eastbound and Westbound Travel Time in seconds for Segment 2

Sample	Eastbound			Westbound		
	Manual	Trimble	GeoStats	Manual	Trimble	GeoStats
1	138	138	137.4	96	97	96.6
2	106	106	105.6	58	58	57.6
3	121	121	120.6	108	108	109.2
4	74	74	73.8	120	121	121.8
5	147	147	*	111	111	112.2
6	83	84	83.4	87	87	87.6
7	65	66	*	63	62	62.4
8	118	118	118.8	86	86	85.8
9	78	78	*	47	49	46.2
10	68	67	67.2	59	60	58.8
11	120	120	119.4	73	72	72
12	73	72	73.2	134	134	135
13	86	85	85.8	74	74	73.2
14	59	58	59.4	70	70	69.6
15	121	121	121.2	107	108	108
16	74	74	*	103	103	103.2
17	105	106	131.4	71	71	71.4
18	154	154	154.8	70	70	70.2
19	136	137	136.2	51	52	51
20	167	167	166.2	48	48	48
21	164	164	165.6	68	69	67.8
22	134	135	134.4	116	115	115.8
23	157	157	157.2	97	97	97.2
24	125	124	124.2	55	54	54.6
25	148	149	148.8	52	52	51.6
26	74	76	75.6	*	50	50.4
27	110	110	110.4	87	88	87.6

* = Data invalid due to human or computer error.

Table A.3: Eastbound and Westbound Travel Time in seconds for Segment 3

Sample	Eastbound			Westbound		
	Manual	Trimble	GeoStats	Manual	Trimble	GeoStats
1	200	200	200.4	172	172	171
2	141	141	141	178	178	178.8
3	144	144	143.4	187	187	186.6
4	250	250	249	126	125	124.2
5	126	122	*	173	174	172.2
6	160	159	159	350	349	349.8
7	217	217	216.6	206	208	207.6
8	126	126	126	197	196	196.8
9	138	137	137.4	186	186	187.2
10	199	200	199.2	213	212	213
11	192	192	192	200	202	201
12	191	191	191.4	148	148	147.6
13	145	145	144.6	171	171	171
14	158	158	157.2	174	174	174.6
15	137	137	136.8	146	146	145.8
16	116	116	*	120	120	118.8
17	154	153	153.6	145	146	145.8
18	178	178	154.2	151	150	150.6
19	113	112	112.8	205	205	205.8
20	147	148	147	194	193	193.2
21	110	109	108.6	243	242	243
22	146	145	144	137	137	136.8
23	236	*	234.6	210	210	210
24	195	196	195	140	140	139.8
25	153	153	152.4	133	134	133.8
26	150	149	148.8	228	229	229.2
27	109	109	108	149	149	149.4

* = Data invalid due to human or computer error.

Table A.4: Eastbound and Westbound Travel Time in seconds for Segment 4

Sample	Eastbound			Westbound		
	Manual	Trimble	GeoStats	Manual	Trimble	GeoStats
1	188	188	186	194	194	194.4
2	169	169	167.4	213	213	212.4
3	185	185	183.6	193	193	192.6
4	187	188	186.6	233	231	234
5	300	304	*	261	260	260.4
6	285	286	285	193	194	193.2
7	358	358	357.6	223	222	221.4
8	266	265	265.2	188	189	187.8
9	265	265	264.6	190	191	189
10	139	138	137.4	178	179	177.6
11	303	303	301.8	163	162	162
12	313	314	312	161	161	160.2
13	252	252	250.2	215	215	214.2
14	333	334	333.6	191	191	190.2
15	348	348	347.4	199	200	199.2
16	224	224	*	259	259	259.8
17	226	227	225	155	139	154.8
18	286	287	307.8	199	200	198
19	213	213	211.2	149	149	148.8
20	208	208	206.4	200	201	200.4
21	210	210	208.8	166	167	165.6
22	210	211	211.2	136	137	136.2
23	211	*	211.2	229	229	228.6
24	258	257	257.4	173	174	173.4
25	245	244	242.4	203	203	202.2
26	166	166	164.4	179	179	178.2
27	233	233	231.6	147	147	146.4

* = Data invalid due to human or computer error.

B. APPENDIX B

DELAY TIME MEASUREMENTS

Table B.1: Eastbound and Westbound Delay Time in seconds for Segment 1

Sample	Eastbound			Westbound		
	Manual	Trimble	GeoStats	Manual	Trimble	GeoStats
1	0	0	0	17	16	15
2	62	56	61.2	13	10	10.2
3	0	0	0	36	37	37.8
4	42	41	43.2	46	46	46.2
5	*	7	*	40	39	39
6	9	7	7.2	3	3	1.8
7	46	45	*	66	65	66
8	16	16	15	0	0	0
9	39	39	*	10	7	7.8
10	66	62	67.2	0	0	0
11	0	0	0	33	32	34.2
12	8	7	7.2	33	32	31.2
13	40	39	40.2	0	0	0
14	29	29	28.2	61	59	60
15	10	11	10.8	35	27	27
16	128	128	*	31	30	30
17	25	25	1.8	20	19	19.8
18	0	0	0	14	13	13.2
19	0	0	0	76	75	75
20	0	0	0	25	35	34.8
21	57	60	60	22	27	27
22	11	8	7.2	75	74	75
23	59	59	58.8	72	72	70.8
24	3	2	1.2	8	6	6
25	0	0	0	37	37	36
26	0	0	0	4	3	3
27	46	45	46.8	26	24	24

* = Data invalid due to human or computer error.

Table B.2: Eastbound and Westbound Delay Time in seconds for Segment 2

Sample	Eastbound			Westbound		
	Manual	Trimble	GeoStats	Manual	Trimble	GeoStats
1	73	72	72	38	38	37.8
2	40	40	40.2	0	0	0
3	53	52	52.8	*	33	31.2
4	6	5	4.8	48	47	46.2
5	*	69	*	36	35	34.2
6	20	19	19.8	21	20	19.8
7	0	0	*	0	0	0
8	50	50	49.2	23	23	22.8
9	26	19	*	0	0	0
10	3	3	1.8	0	0	0
11	48	45	43.8	15	13	13.2
12	0	0	0	60	56	58.2
13	0	0	0	14	13	13.2
14	0	0	0	0	0	0
15	48	46	46.2	34	33	33
16	10	10	*	29	28	28.2
17	43	43	66	4	3	3
18	88	88	88.2	4	3	3
19	73	71	70.8	0	0	0
20	101	96	96	0	0	0
21	102	101	100.2	0	0	0
22	67	67	66	32	28	27
23	79	76	76.2	32	27	28.2
24	56	55	55.8	0	0	0
25	58	68	70.2	0	0	0
26	14	13	13.2	0	0	0
27	38	38	37.8	15	13	13.2

* = Data invalid due to human or computer error.

Table B.3: Eastbound and Westbound Delay Time in seconds for Segment 3

Sample	Eastbound			Westbound		
	Manual	Trimble	GeoStats	Manual	Trimble	GeoStats
1	52	47	49.2	39	39	37.8
2	5	4	4.2	60	59	58.8
3	13	11	12	61	60	61.2
4	109	107	106.8	0	0	0
5	0	0	*	31	30	28.8
6	14	13	13.8	173	*	172.2
7	65	62	63	82	79	79.2
8	0	0	0	52	52	51
9	3	2	3	71	70	70.2
10	70	68	67.8	57	55	54
11	57	56	57	71	70	70.8
12	29	28	27	15	15	13.8
13	15	13	13.8	52	51	51
14	16	14	13.8	27	26	25.8
15	0	0	0	18	17	16.8
16	0	0	*	0	0	0
17	10	9	7.8	18	17	16.8
18	37	36	15	30	30	31.2
19	0	0	0	73	73	73.2
20	21	20	21	56	53	54
21	0	0	0	105	103	103.2
22	14	14	13.2	15	13	12
23	102	*	102	46	46	46.2
24	49	45	46.2	4	3	3
25	9	9	7.8	12	12	10.8
26	14	14	13.2	80	79	79.2
27	0	0	0	25	23	24

* = Data invalid due to human or computer error.

Table B.4: Eastbound and Westbound Delay Time in seconds for Segment 4

Sample	Eastbound			Westbound		
	Manual	Trimble	GeoStats	Manual	Trimble	GeoStats
1	32	32	31.2	35	35	34.2
2	0	0	0	43	42	40.8
3	13	13	13.2	30	29	28.8
4	16	16	16.2	49	48	48
5	135	134	*	84	81	82.2
6	93	92	93	24	23	22.8
7	172	170	169.8	44	43	43.2
8	97	96	96	26	25	25.8
9	125	124	124.2	40	38	39
10	0	0	0	4	3	4.2
11	120	118	117	13	13	13.2
12	143	142	142.2	12	11	10.8
13	72	71	70.2	51	49	49.8
14	163	162	160.8	30	30	28.8
15	151	150	151.2	51	50	51
16	34	33	*	87	80	79.2
17	28	24	24	0	0	0
18	116	119	139.8	34	32	33
19	49	46	46.8	0	0	0
20	43	41	40.8	35	36	36
21	53	51	52.2	0	0	0
22	32	31	28.8	0	0	0
23	156	*	52.8	33	32	33
24	70	66	64.8	0	0	0
25	56	67	67.2	29	28	28.2
26	8	7	7.8	0	0	0
27	75	71	70.8	0	0	0

* = Data invalid due to human or computer error.

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