Evaluation of Physical Improvements Made Across a Signalized Campus Arterial

by

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Abstract

The objective of this research was to develop and evaluate a methodology for measuring the traffic and pedestrian effects of new physical improvements made to Donahue Drive, a signalized arterial on the campus of Auburn University. A before and after study was performed on three types (i.e., parameters) of collected field data: (1) vehicular volume, (2) vehicle spot speeds, and (3) travel times. Steps are outlined for data collection, processing, and performing the analyses for each of the three parameters. Various types of analyses were used to evaluate the effects of the physical improvements on each collected parameter. T-tests were used to analyze the effects of the improvements on the vehicular volume and speed measurements while a nested ANOVA was used to evaluate the travel time data. The methodology for collecting and analyzing the traffic and pedestrian framework was created with the intent of use on future signalized arterial improvements.

Acknowledgements

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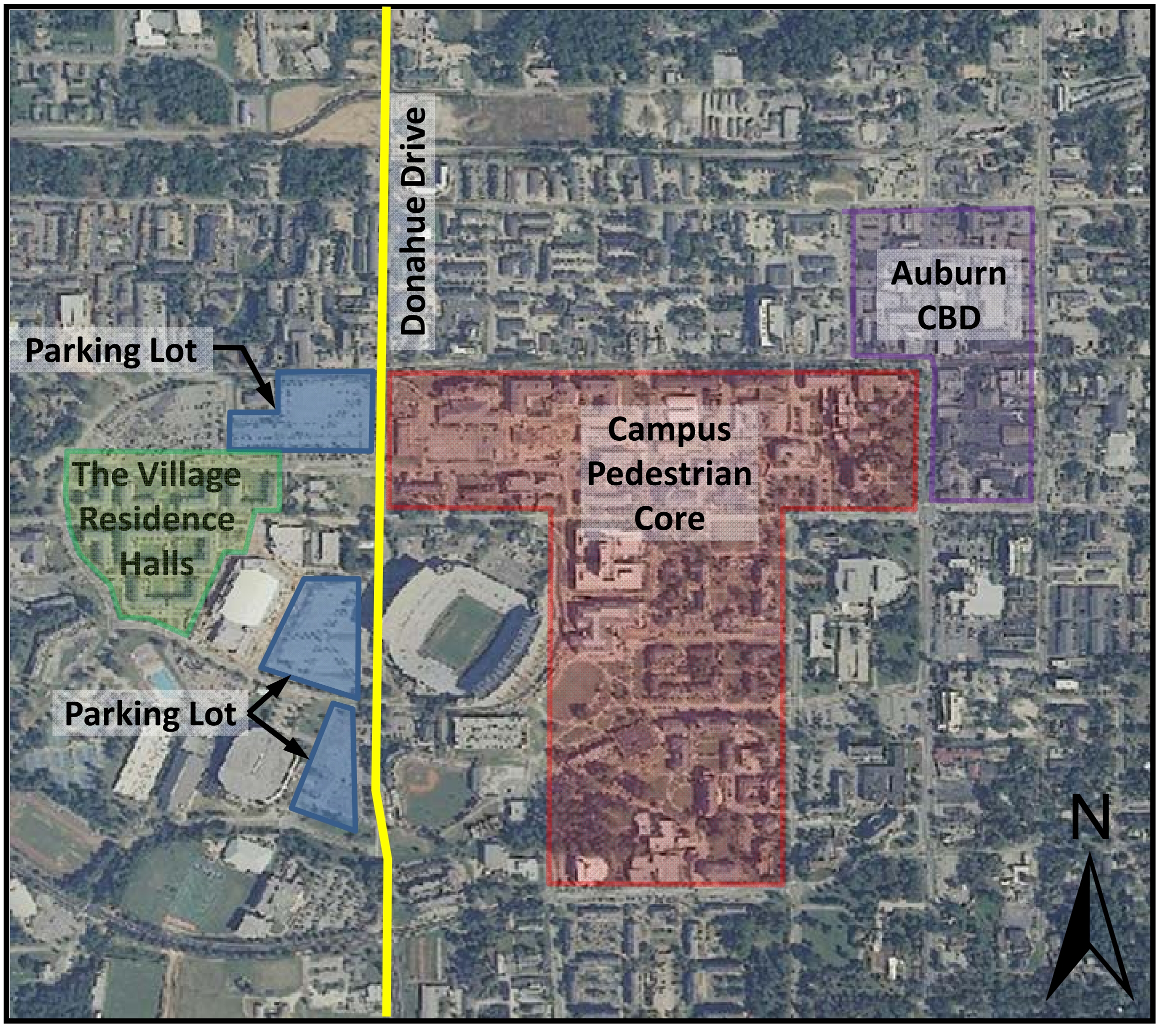
Chapter 1: Introduction

1.1 INTRODUCTION

Urban street improvements (e.g., traffic signal coordination, installation of new intersections, and installation of traffic calming measures) are often designed to improve traffic flow and minimize congestion-related delay while increasing pedestrian safety. University campus roadways usually consist of a number of signalized intersections along with a multitude of pedestrian crosswalks that tend to impede the flow of traffic. During campus peak hours (i.e., early morning or late afternoon), the majority of students and faculty may be traveling to or departing from campus placing an increased demand on the campus transportation system. Campus roadways experience high volumes of vehicular traffic comprised of single occupancy vehicles (SOVs), high occupancy vehicles (HOVs), and transit vehicles, coupled with crossing or conflicting traffic from both pedestrians and bicyclists. Traffic planners and operators are constantly challenged to maintain steady vehicle traffic throughput on arterials during periods of congestion and ensuring pedestrian and bicyclist safety. This problem is compounded when a series of intersections exist in close proximity to each other. A comprehensive signal coordination effort is perhaps one of the best options for alleviating a corridor's traffic congestion problems. Signal coordination links a series of traffic signals together to ensure the most efficient throughput for the corridor under consideration. Since signals are linked with other signals in the corridor section, signal phases are actuated based on communication from both upstream and downstream signals within the system. The impact of signal coordination can be difficult to fully quantify for all aspects of a roadway. For instance, while flow may increase on the corridor where the coordination was performed, it may reduce throughput on intersecting arterials and collectors. Additionally, while speed may increase on the corridor, higher speeds may sacrifice pedestrian and bicycle safety.

1.2 Background

In recent years, efforts to transform Auburn University's campus into a more pedestrian and bicycle friendly environment have been very successful. Several streets on campus have been closed to vehicular traffic and converted into pedestrian concourses. Student parking capacity has been reduced, limiting the number of SOV trips. Ridership on the campus transit system, Tiger Transit, has increased as a response to limited on-campus parking and improvements in overall transit efficiency. The closing of two east/west streets and one north/south street has created a campus pedestrian-friendly core minimizing vehicle-pedestrian conflicts on-campus. Donahue Drive makes up the western boundary of the pedestrian core and experiences high vehicle traffic and crossing pedestrian volumes trying to gain access to the campus core. The two most popular student parking facilities can be accessed from Donahue Drive. This adds to both vehicle congestion on the corridor and pedestrian congestion crossing the corridor in an attempt to access the campus core. The completion of new student dormitories, the Village, on the western side of Donahue has also lead to more pedestrians crossing Donahue Drive into campus. Figure 1.1 depicts the campus pedestrian core along with several large generators of pedestrian volume entering campus from the western boundary, Donahue Drive.



Note: CBD = Central Business District

Figure 1.1 Campus Pedestrian Core with Pedestrian Generators

Additionally, Donahue Drive receives a large volume of nonstudent through-traffic because of its proximity to the central business district (CBD) of the City of Auburn. For these reasons, Donahue Drive experiences significant levels of congestion involving queuing at several of its intersections. Figure 1.2 illustrates the corridor in its pre-improvement condition.

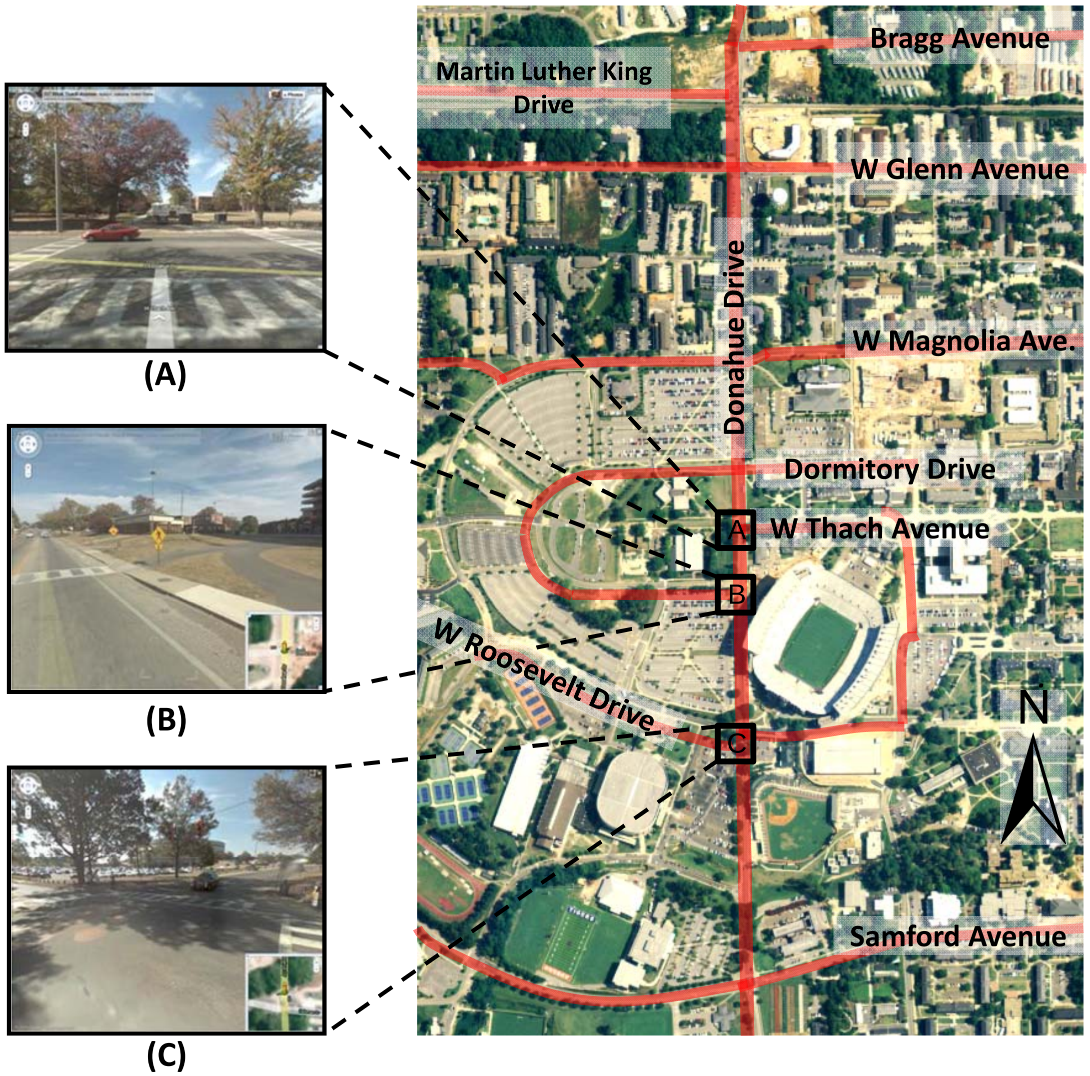


Figure 1.2 Aerial Photograph of the Traffic Landscape before the Implementation of Arterial Improvements

Figure 1.2 also shows the three intersections experiencing the largest congestion problems which are labeled as intersections (A) Donahue Dr. | W. Thach Ave., (B) Donahue Dr. | Dormitory Dr., and (C) Donahue Dr. | W. Roosevelt Dr., respectively. Intersection A, in the pre-improvement scenario, was the departure point for Tiger Transit and featured a four-way stop. Pedestrian and vehicle congestion was so substantial that the university employed a crossing guard during school hours to control both vehicle and pedestrian traffic. This vehicle and pedestrian congestion led Auburn University and the City of Auburn to institute two phases of arterial improvements on Donahue Drive.

Phase I improvements, completed during the Summer of 2010, were implemented to immediately increase pedestrian safety crossing the corridor by decreasing vehicular speeds, especially at the Donahue Dr. | W. Thach Ave. intersection. Phase I improvements include:

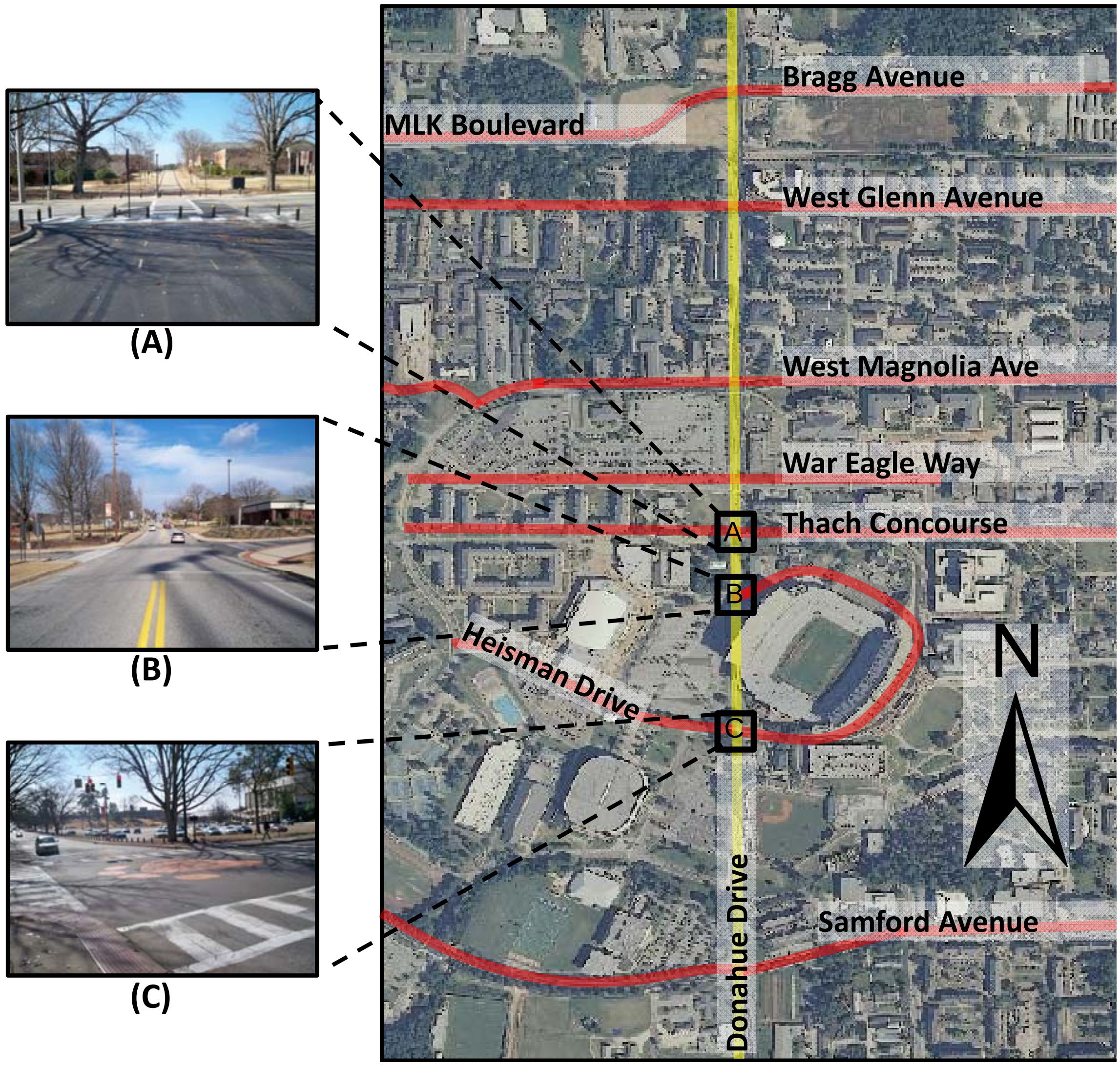
(1) the completion of Heisman Drive which loops around Jordan Hare Stadium to facilitate Tiger Transit departures and arrivals,

(2) the conversion of West Thach Avenue into a pedestrian-only concourse. This was allowed by the completion of Heisman Drive., since West Thach Avenue previously was used to serve the Tiger Transit system,

(3) the removal of two crosswalks both running east to west across Donahue Drive on either side of the W. Thach Pedestrian Concourse,

(4) the installation of a central speed table with an integrated raised pedestrian crosswalk on the Thach Pedestrian Concourse to replace the two crosswalks that were removed, and

(5) an addition of permanent protective/permissive signal phasing as well as the installation of pedestrian features to the intersection of Donahue Dr. and South Heisman Dr. (formerly W. Roosevelt Dr.) (Intersection C in Figure 1.3).



Notes:
1) Roads are shown in red
2) Pedestrian only corridors are shown in yellow

Figure 1.3 Aerial Photograph of the Traffic Landscape after the Implementation of Phase I Intermediate Arterial Improvements

Phase II improvements, which are scheduled to be completed during November 2011, were aimed at improving traffic flow on the corridor and include:

(1) the installation of a pedestrian signal at the intersection of the W. Thach Pedestrian Concourse to allow pedestrians to cross Donahue Dr,

(2) the installation of a new traffic signal at the newly formed intersection of N. Heisman Drive and Donahue Dr. (Intersection B in Figure 1.3).

(3) the implementation of signal coordination for 8 signalized intersections on Donahue Drive. The intersections include, from North to South; (1) Martin Luther King Drive | Bragg Avenue, (2) West Glenn Avenue, (3) West Magnolia Avenue, (4) War Eagle Way, (5) W Thach Ave, (6) Heisman Drive, (7) Roosevelt Drive, and (8) Samford Avenue,

(4) incorporating three additional signals on Wire Road into the overall coordination on Donahue Drive. The intersections on Wire Road include from North to South: (1) Magnolia Drive, (2) W Thach Avenue, and (3) Heisman Drive. These intersections can be seen in Figure 1.4.

Figure 1.3 shows the traffic landscape after Phase I improvements were implemented. These improvements were necessary to reduce the queuing problems occurring during peak campus hours. However, the improvement's complete effectiveness is not easily identifiable and thus requires an in-depth before-and-after analysis.

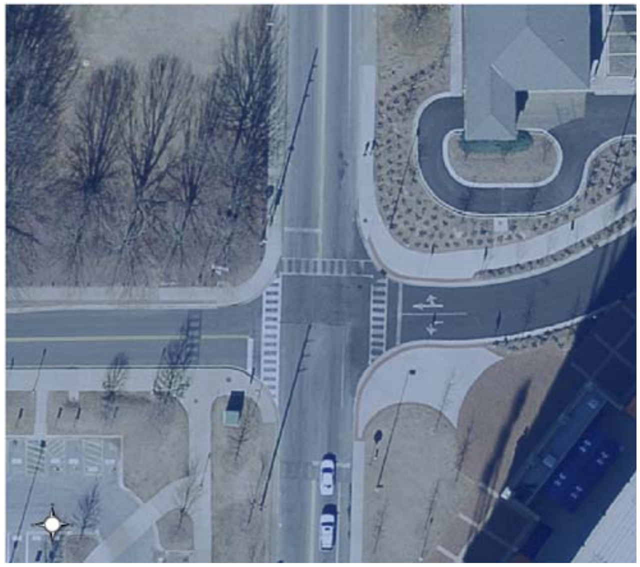
Figure 1.4 Wire Road Intersections added to the coordination on Donahue Drive

1.3 Terminology

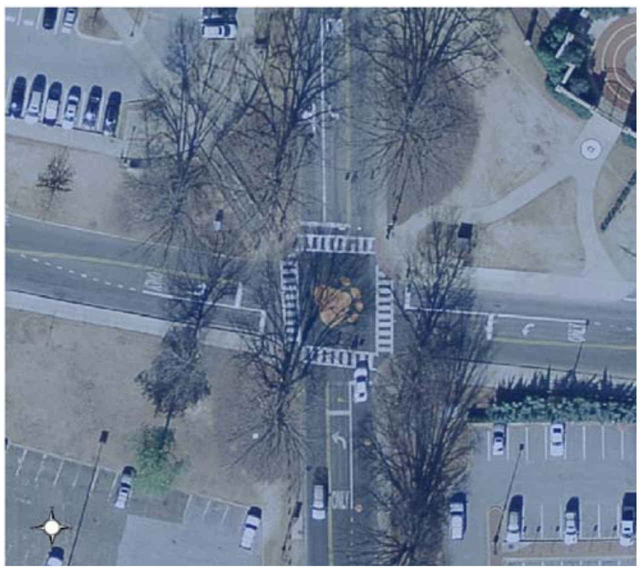
This section is designed to establish a common nomenclature for the various traffic facilities referred to throughout this report. In Figure 1.3, Intersection A will be referred to as the 'West Thach Pedestrian Crossing'. This concourse features the speed table with an integrated raised pedestrian crosswalk referred to in the previous section, as shown in Figure 1.5. Intersection B will be referred to as 'North Heisman Drive Intersection'. As previously stated in Section 1.2, this intersection was signalized to aid Tiger Transit buses departing their hub station entering Donahue Drive. Intersection C will be referred to as 'South Heisman Drive Intersection'. Both intersections are shown in their post final improvement state in Figure 1.6. Other changes include War Eagle Way, which was formerly known as Dormitory Drive. Additionally, the intersection where Donahue

Drive meets Martin Luther King Drive and Bragg Avenue will be referred to as the 'Bragg Avenue Intersection'.

Figure 1.5 Speed Table w/Integrated Raised Pedestrian Crosswalk at Thach Pedestrian Concourse



(a) North Heisman Drive Intersection



(b) South Heisman Drive Intersection

Figure 1.6 Post-Improvement Layout of Heisman Drive Intersections

1.4 Research Objectives

The research presented herein is based on an effort by the Department of Civil Engineering at Auburn University and the Highway Research Center (HRC) to study and evaluate the arterial improvements made on Donahue Drive. The intent of this research is to expand on a Federal Transit Administration (FTA) campus transportation study at Auburn University which focuses on campus-wide improvements regarding transit, bicycling, pedestrian, and parking issues. The main objective of this study is to quantify the traffic flow improvements made by implementing several arterial improvements. A secondary objective is to assess whether pedestrian safety has been improved by minimizing pedestrian-vehicle interactions along the corridor. The research effort was divided into the following tasks to satisfy the abovementioned research objectives are as follows:

Research Tasks

1. Identify, describe, evaluate, and critically assess pertinent literature on before-and-after traffic studies, travel time collection methods using the global positioning system (GPS), and speed-volume studies using pneumatic traffic counters,

2. Collect speed and volume data using pneumatic traffic counters at four locations between signal intersections along Donahue Drive over the course of a week during the pre-improvement, Phase I improvement, and Phase II improvement data collection periods,

3. Design and implement a method for collecting travel times along the corridor using a GPS-based tracking method, and

4. Capture the pre-improvement, Phase I improvement, and Phase II improvement landscapes of the traffic and pedestrian facilities with digital photograph and develop a photo library.

5. Conduct a comparative statistical analysis on all data collection periods speed and volume data,
6. Process the raw GPS data by: (1) filtering out error points, (2) carrying out the developed procedures to process the data into travel times, and (3) performing a statistical analysis on the data collected during all collection phases,
7. Verify and comment on the relationship between the speed study and travel time study results, and
8. Visually analyze the digital photographic library to determine whether pedestrian safety was improved from a practical engineering perspective after the new traffic facilities were implemented.

1.5 Organization of Thesis

The thesis is organized into 4 additional chapters. *Chapter 2* highlights the existing literature that was reviewed in developing an architecture for testing and evaluating the improvements made to the corridor. The literature review is divided into two sections. The first part focuses on the various types of travel time studies with a further emphasis on travel time collection using GPS devices. The other section highlights before-and-after case studies that have been performed on corridors which have undergone traffic signal coordination. For the case studies in both sections, the field collection parameters and the methods for analyses are examined and compared.

Chapter 3 introduces the methods for data collection and data analysis for the study. This chapter introduces the three study parameters: vehicular volume collection, speed collection, and travel time collection. The first section focuses on the data collection procedures for each of the three study parameters, such as the time of collection, location, peak period, and number of observations collected. The second section highlights the methods of analyses and the procedures for processing the raw data. Each study parameter was given a different type of analysis to best reflect the changes that occurred across improvement periods by isolating other factors (e.g., peak period, location, direction, etc.).

The results and analysis of the field studies are presented in *Chapter 4*. *Chapter 4* is organized into sections based on the three study parameters: vehicular volume, speed, and travel time. The field results of each before-and-after study are introduced and analyzed based on the framework outlined in *Chapter 3* for each of the parameters.

Volume was analyzed first to determine whether any increase/decrease in vehicular demand on the corridor influenced the travel time and speed results.

Chapter 5 includes the conclusions drawn from each of the different analyses. It is further divided by the three parameters studied. Additionally, *Chapter 5* includes recommendations for future research.

Chapter 2: Literature Review

2.1 Introduction

The effectiveness of arterial improvements (i.e., a signal coordination) can be measured and evaluated through a number of means which are dependent on the length, volume, and location of the corridor under consideration. Determining which method of data collection to use can maximize the efficiency of the overall research study. This literature review examines both speed and travel time studies performed by research groups and State Departments of Transportation (DOTs) under a variety of circumstances. The literature review first focuses on the various types of methods for collecting speed and traffic flow during travel time studies. Several case studies involving the global positioning system (GPS) test vehicle method are compared and contrasted to emphasize the variation in procedural test methods. The second part of the literature review involves the implementation and evaluation of a corridor traffic signal coordination. The types of data collection, test methods, and methods of analysis are compared and contrasted for each study.

2.2 Travel Time Studies

Travel time is a traffic measurement that determines the amount of time for a vehicle to traverse a given section of roadway. It is a very valuable measurement because it allows traffic engineers to measure the effectiveness of a traffic system, and is easily understood by the public. Travel time delay is the difference between the actual travel time to traverse a section of roadway and the driver's expected or desired travel time. However, travel time delay is seldom used by traffic engineers because there are no accurate methodologies for determining the expected travel time of a motorist. Travel time studies are most often performed on corridors with one or more points of congestion to evaluate a corridor's overall effectiveness. Travel time studies may also be performed to identify problem locations (e.g., locations experiencing extensive queuing as a result of ineffective signal phasing) on traffic facilities. In many cases, intersection to intersection travel times (a.k.a. link travel times) are used to further identify problem locations. Link travel time is the time it takes to travel from one intersection to the next. It can be used in almost every type of travel time study.

There are a variety of methods for performing travel time studies. These methods can be grouped into roadside techniques and vehicle techniques (Quiroga and Bullock 1999). Roadside techniques use devices placed along the side of routes being studied, such as inductive loops or closed circuit television cameras to record travel time (Quiroga and Bullock 1999). However, these techniques are becoming less popular as they have estimated traffic speed with an error percentage approaching 10% (Miller et al., 2010). Vehicle techniques use people or detecting devices inside a test vehicle to record the time it takes the test vehicle to pass selected points (Quiroga and Bullock 1999). Moreover, test vehicles can be active or passive (Yang 2005). Active test vehicles are instrumented with a means of collecting position and time and travel a pre-determined route for the purpose of collecting travel time measurements (Yang 2005). Conversely, passive test vehicles are vehicles that are already part of the traffic stream and happen to be travelling down the sample corridor under consideration (Yang 2005). Devices such as mobile phones or GPS navigation systems may be used to access travel times for passive test vehicles (Yang 2005). Although the accuracy is still suspect, current intelligent transportation system (ITS) infrastructure can utilize the GPS on mobile phones or navigation devices to access real-time travel times (Yang 2005). A great deal of the studies performed on active test vehicles use them as a controlled parameter for developing passive test vehicle architecture for evaluating travel times. This thesis will primarily address active test vehicle methods to satisfy the objectives of the study. Currently, there are two main active vehicle techniques for collecting travel times: (1) the manual method and (2) the GPS test vehicle method which are both discussed in the following sections.

2.2.1 The Manual Method

The manual method for collecting travel time relies on an observer in the passenger seat along with the driver. The driver abides by a set of predefined driver instructions and a predetermined route (Yang 2005). The observer records the time when the vehicle passes predefined checkpoints along its route (Yang 2005). Therefore, travel time can be computed between the checkpoints or for the cumulative roadway section. Small errors may occur as a result of human error in executing the manual method while recording times at checkpoints (Miller et al., 2010). Additionally, it is inherently much more labor intensive than using travel time detection devices.

2.2.2 The GPS Test Vehicle Technique

Another method for collecting travel times is the GPS test vehicle method. This method uses a test vehicle instrumented with a GPS device mounted to it. The GPS device records the vehicle's position and speed at selected time intervals as the test vehicle travels down a selected corridor. This method has proven to be more efficient and accurate than human systems because the GPS device collects the data without needing a second person in the passenger seat. Travel time can be computed by algorithms or manually by integrating the data from the GPS device into a geographic information system (GIS). The GIS software has the ability to overlay the GPS data onto maps or aerial photos allowing for travel time between two reference points to be computed. The next section will highlight a number of studies that use this method.

A group of researchers from the Florida Department of Transportation and Florida State University developed a set of guidelines for collecting travel time studies using GPS technology in 2004 (Ngo-Quoc et al., 2004). The data collection time guidelines included such factors as what month of the year, day(s) of the week, and time-of-day to perform the study. Typical annual traffic conditions were recommended for selecting the month to perform data collection (i.e., during the middle of the fall or spring semester for a university setting). Middle weekdays (i.e., Tuesday, Wednesday, and Thursday) were recommended as collection days because Monday and Friday usually experience large variations in traffic volume. Additionally, the researchers recommended that holidays should be avoided. Peak periods, which usually consist of an A.M. and P.M. peak, were generally used by most researchers as collection times. The researchers also developed a set of procedures and formulas for determining the number of runs required to collect per time-of-day periods in order to achieve statistical significance. The procedures and formulas can be seen in Appendix A. The report also recommends that driver guidelines be written and carried out accordingly. The guidelines recommend a technique to mirror the speed of average drivers on the roadway, while not driving over-aggressively.

2.2.2.1 Applications of the GPS Test Vehicle Technique

In a study done at the Georgia Institute of Technology, Hunter et al. (2006) determined procedures for determining travel times using the GPS test vehicle method. Their procedures included configuring a test vehicle, selecting travel time routes, creating driver instructions, determining necessary sample sizes, and conducting a pilot study. They selected an urban arterial corridor to evaluate a newly installed signal coordination of 15 intersections on Atlanta Road, Paces Ferry Road, and Cumberland Park. Four different drivers drove a total of 755 fixed-route runs, of which 97.5 % (736 runs) of the data was processed. 2.5% of the data was discarded after screening for error points. Error points were data stamps that did not fall into a set of parameters such as: (1) too great or too little distance between points, (2) too high of an acceleration rate, too high of horizontal dilution of precision (HDOP), or readings based on an insufficient amount of satellites. (Kim et al., 2006). Route design was a very important aspect during the testing. Since one of the objectives of this study was to determine intersection approach performance, the authors decided to not just use end-to-end travel runs (Hunter et al., 2006). End-to-end runs do not provide information on side-street approach delays. Therefore, the study used random routes in addition to the aforementioned fixed routes. During the random routes, the test vehicle drivers were given a random origin and destination (O-D) intersection pair to traverse, making each travel time run begin and end on the intersection side streets off the study corridor. The goal of the random routes was to have a unique travel time for each O-D intersection combination available for users of the corridor whom only need to traverse a portion of the corridor.

After data collection, each data point is given a unique ID containing a run number, O-D intersection pair, date, and time. Once the error points had been filtered out and interpolated values had been inserted into their place, the data was placed into the travel run intersection passing time identification (TRIPTI) algorithm. This algorithm was essential in computing travel times for the O-D intersections. TRIPTI used reference lines that run through the intersection to delineate segments along the corridor. Next, the algorithm located the two points on either side of each reference line and recorded the time when the points were passed. Therefore, travel time is computed by subtracting the time recorded at the first data point in the segment from the time recorded at the last data point in the segment. The TRIPTI algorithm calculated the travel time for every intersection pair before signal improvements were installed (Hunter, Seung et al. 2006).

Another study implementing the GPS test vehicle method was performed at the University of Minnesota by Yang (2005). This application of the GPS test vehicle method involved calculating the travel time of an urban arterial during special events. The arterial experiences significant congestion during special events held at the Duluth Entertainment and Convention Center (DECC). Researchers used the GPS test vehicle method to collect after-event travel times which were processed in real-time using the Kalman filter algorithm, which eliminated inaccuracies over time. The purpose of the study was to aid the Minnesota Department of Transportation (Mn/DOT) in a more efficient management method for special event traffic flow. The results of the study provided the researchers with the potential to output real-time travel times so users could select different routes and/or traffic operators could temporarily adjust signal coordination (Yang 2005).

A 2.17 mile (3.5 km) stretch of the arterial exiting the DECC was divided into three segments separated by signalized intersections. Three test vehicles were used to report both the end-to-end travel time as well as the link travel times. These vehicles left at three minute intervals following the conclusion of a special event. Once each vehicle reached its destination, it returned back to its original point and started its next run. This process continued until traffic conditions returned to normal. Once the GPS receiver collected a data point, it used a radio transmitter to send the data back to the base station. At the base station, a laptop computer was used to implement the Kalman filter model which computed the travel times measured by the test vehicles. The model incorporated the measured travel times into generating predicted travel times. Collection was performed for special events held at the DECC over a seven-month period (Nov 2003-May 2004). Data collection took approximately 45 minutes, with about 15 total runs recorded per event. The author concluded that the low number of test vehicles had a significant effect on the performance of the study, however, more test vehicles would drive up the entire operation cost (Yang 2005).

A similar study conducted by Miller, et al. (2010) was performed in Anchorage, Alaska to test several methods of collecting travel time with a GPS device. Since the majority of roads tested are traffic regulated (as opposed to free flowing), using the average speed was ineffective in determining travel time. When a vehicle is stopped at a traffic signal, a reported speed of 0 mph (0 km/hr) occurs, thus greatly impacting the average travel time. This study used the GPS test vehicle method with several important variations. Most notably, the GPS devices mounted on the test vehicle recorded the position and speed at varying time increments to analyze the effect on travel time. Stamps for position, speed, and direction were taken every 10 seconds and transmitted to a central server. The data were then inputted into two algorithms, the speed model and the proportional model. The speed model averages the speeds measured in a segment, or edge, of the sample roadway section. It takes the length of the segment and divides it by the average speed in the segment to compute the travel time. Thus, while position and direction are used in determining which segment of the roadway the data is from, speed is the most important element in this algorithm. The proportional model uses an algorithm "to proportionally determine the amount of time to traverse an edge (segment) based on the times and locations of certain data points for an individual vehicle" (Miller et al., 2010). Since the device was collecting data every 10 seconds, the beginning and end of segment may not have been represented in the data. Therefore the proportional algorithm was needed (Miller et al., 2010).

Twenty-two probe vehicles traveled along the Anchorage arterial at two peak periods, from 7:00 a.m. to 9:00 a.m. and 4:30 p.m. to 6:30 p.m. (Miller et al., 2010). For each sample segment, the driver of the vehicle carried out the manual method for calculating travel time. The manual method served as the control variable to compare against the speed and proportional models. Additionally, the amount of time between data point collection was varied by 10 second increments up to 60 seconds. Since all the devices in the probe cars collected data every 10 seconds, simulating a device that collected data every 20 seconds was carried out by eliminating every other data point during processing. The same process was done for 30, 40, 50, and 60 second transmissions respectively. Figure 2.1 shows the calculated percent difference between the two models and the actual time to traverse the roadway segment. The actual time to traverse the roadway segment was averaged using the manual method by the 22 probe vehicles to be 148 seconds.

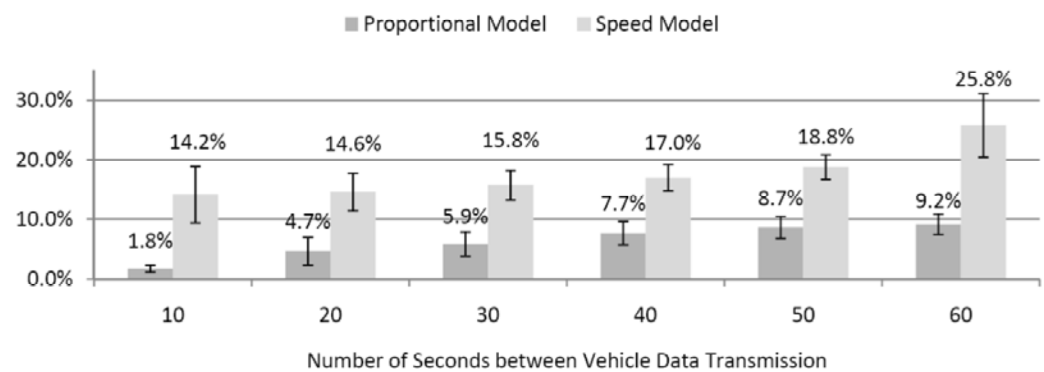


Figure 2.1 Average Percentage Difference Between Calculated Time and Actual Time to Traverse, Including 95% Confidence Intervals (Miller et al., 2010).

The results show that the proportional model is obviously much more effective for calculating the travel time than the speed model. Also, as the amount of time in between vehicle data transmissions increases, the percentage of error from the actual travel time increased. Both of these outcomes were somewhat expected. The speed model produced more accurate results on non-signalized highways or freeways. However, since the roadway tested was a signalized arterial, the proportional model was far more accurate. At 10 second data point transmissions, the proportional model gave an error of only 1.8%, which was deemed very accurate. The slight error is probably due to how close to the beginning and edge of the segment that the transmissions occurred. Additionally, because human drivers were executing the manual method to give the actual time, a small error should be attributed to human errors. The author concluded that the closer the transmission to the edge of the segment, the more accurate both models became (Miller et al., 2010).

Another travel time data collection using the GPS Test Vehicle technique was carried out on a Duluth, MN arterial by Billings and Yang (2006). They used GPS collected travel times in modeling a predictor for travel times on the same corridor using the autoregressive integrated moving average (ARIMA). The test site was a 3.7 mile (5.95 km) stretch of the Minnesota State Highway 194 Corridor that runs through the center of the Duluth metro area. The site was selected because its 10 intersections experience some of the largest amounts of congestion in the area. Speed limits varied from 30 to 40 mph (48.3 to 64.4 km/hr) down the corridor. One test vehicle was equipped with a GPS device that received GPS signals for longitude, latitude, speed, direction, time stamp, and date. The test vehicle collected data during the weekday rush hour (3:30 to 5:00p.m.) for an eight month period (Oct 2004 to June 2005). The Cohen Sutherland line-clipping algorithm, an algorithm that divides a 2D space into 9 regions in computer graphics, was used to determine the location and time when a vehicle entered a new intersection (Billings and Jiann-Shiou 2006). Intersections were treated as squares in space; therefore, the travel time was computed for each intersection and for each roadway segment in between the intersections. Once again, the time stamps corresponding to the values closest to the edge of each square were used as the beginning and ending points. These observed values were then plugged into the ARIMA model to generate accurate travel time predictions for each section (Billings and Jiann-Shiou 2006).

Quiroga and Bullock (1999) created a database management system for large-scale applications of the GPS test vehicle method for collecting travel times. This research discussed the issues of processing more than 2 million GPS data points collected in Baton Rouge, LA (Quiroga and Bullock 1999). The GPS receivers used in the study had the capability of collecting speeds, coordinates, and time at 1 second intervals. Since the probe vehicles travelled on a variety of different corridors around Baton Rouge, Quiroga and Bullock used a different architecture for linearly referencing GPS data by using dynamic segmentation tools. These dynamic segmentation tools allowed for the travel time studies to be executed at various levels of resolution. The different levels of resolution indicate that travel time studies can be executed for entire regions as well as individual intersections. The segmentation tools involve calculating the average speed down a segment by using a special case of the trapezoidal rule where time intervals can be variable. Additionally, several other formulas were used to obtain correct travel times. These formulas reduce the sensitivity of the mean segment speeds to outlying low speeds caused by adverse travel conditions. Therefore, when a vehicle is stopped for a length of time in a segment, the low speeds will not greatly influence the mean speed. Travel time runs were performed at three different time periods: the AM peak, the PM peak, and an off-peak period. The number of runs varied for each time period based on the specific error tolerance specifications in the computation of mean speeds. Once runs were completed and calculations for travel time and mean speed were computed using various applications of the trapezoidal rule, the data were processed into a geographic relational database. Microsoft Access and Caliper TransCAD were used to implement the database scheme, which allows users to build queries to access travel times based on time, date, peak period, segment code, and roadway code. A total of 428 GPS data files were processed into 1.8 million GPS stamps on a 151 miles (243 km) highway network. The procedures detailed in this study were meant to be used by city traffic officials and planners for conducting travel time studies. The procedures addressed one of the main technical issues faced in travel time studies: proper indexing, storing, and retrieving of data when millions of GPS stamps were collected (Quiroga and Bullock 1999).

Table 2.1 summarizes the GPS Test Vehicle method literature that was reviewed in this section. The table offers the most important categories that were evaluated for developing an architecture to implement the GPS Test Vehicle method on Donahue Drive. Collection period and collection time (time of day) were among the most important parts of the architecture development taken from the literature. Since the GPS Test Vehicle method is widely used, the studies shown in the table have a variety of different purposes.

Table 2.1 Summary of Experimental Applications of the GPS Test Vehicle Method for Computing Travel Times from Literature

Studies	Location / Roadway Information	Probe Vehicles	Collection Period	Collection Times	Purpose of the Study
(Hunter, Seung et al. 2006)	Both directions of an urban arterial through downtown Atlanta, GA with 15 intersections	4 vehicles collected over 755 fixed-route runs	Collected over 6 weekdays and 4 weekend days	• weekday morning peak • weekday morning off-peak • weekday afternoon peak • weekday evening peak • weekends	• Developed a procedure for collecting travel time data on urban arterials using a GPS device • Developed a procedure for processing the data using the TRIPTI algorithm, database development, and statistics calculation • Measured travel times for the pre-implementation setting of a planned signal coordination on the Atlanta arterial
(Yang 2005)	3.5-km urban arterial through Duluth, MN with 3 intersections downstream of the	3 test vehicles leave at 3 minute intervals after the end of the event	Collected over a seven-month period (Nov 2003-May 2004)	• Collected during special events at the nearby DECC until traffic reaches normal conditions (Approx. 45 minutes in most cases)	• Used the real-time travel time results to generate a travel time predictor based on the Kalman filter to be used by traffic officials during special events at the DECC
(Miller, Kim et al. 2010)[1]	0.99 mile(1.59-km) signalized arterial in Anchorage, AK that is heavily congested	22 test vehicles	UNK	• Morning Peak Period 7:00a.m. – 9:00p.m. • Evening Peak Period 4:30p.m. – 6:00p.m.	• Tested two different algorithms, the speed model and proportional model, against the manual method performed by the test vehicle drive • Compared the accuracy of varying the transmission periods of the GPS device
(Billings and Jiann-Shiou 2006)	0.37 mile heavily congested urban arterial in Duluth, MN with 10 signalized intersections	1 test vehicle	Collected over an eight-month period (Oct 26, 2004 – June 24, 2005) during weekdays	• Evening Peak Period: 3:30p.m. – 5:00p.m.	• Used the GPS test vehicle technique for calculating travel time as a parameter entered into the ARIMA model to predict section travel time on the corridor
(Quiroga and Bullock 1999)	243-km of highway network in Baton Rouge, LA	UNK	UNK	• Data is collected in 2 hour blocks.	• Developed a set of procedures for conducting travel time studies to be used by city traffic officials and planners • Created a database management system for proper indexing, storing, and retrieving of data in an environment where millions of GPS records may be collected • Introduced dynamic segmentation technique for determining when a vehicle enters and exits a route

Notes: '1' GPS device collected position points at 10 second intervals rather than every second
UNK = Unknown

2.3 Signal Coordination

On arterials where intersections are closely spaced and traffic volumes are high, congested conditions may occur causing large queues that disrupt motorist progression. Rather than increasing vehicle capacity by adding lanes, traffic engineers apply coordinated traffic signal control systems to the corridor to improve overall throughput efficiency. The *2009 Edition of the Manual on Uniform Traffic Control Devices* (MUTCD) recommends that all traffic signals within 0.5 miles to be coordinated under a common cycle length (MUTCD 2009). Coordinated signal systems help to minimize the amount of stops vehicles must make while traveling down a corridor, thus reducing travel delay. When upstream traffic arrives at an intersection, the traffic signal should ideally turn green allowing for most of the traffic to progress through multiple intersections. In practice, coordinated systems do not always meet their goals because of outdated offsets or short-term variations in traffic volume. Considerations for design components include hardware limitations, pedestrians, phase sequences, an early return to green, heavy side street volumes, turn bay intersections, and oversaturated conditions. Coordinated systems are widely preferred by traffic engineers over isolated (non-coordinated) signal systems. However, quantifying the benefits of a coordinated system as compared with isolated signal systems is still a widely discussed topic. The following section will discuss several case studies that implemented coordinated traffic signal systems which were evaluated to assess overall improvements in performance.

2.3.1 Signal Coordination Case Studies

2.3.1.1 Virginia Transportation Research Council Study on the Benefits of Coordinated Traffic Signals

Several before-and-after studies have been performed on arterials with newly installed signal coordinations. A study to quantify the benefits of the signal coordination effort in two counties in Virginia was performed by the Virginia Transportation Research Council (Chen and Park 2010). Site 1, located in Gloucester County, was selected solely to quantify the benefits of the signal coordination using before-and-after corridor travel times and approach delays. Site 1 was located on Route 17 and contained 5 isolated signalized intersections before the signal coordination was installed. Site 2 was located in Chesterfield County on US 60 and featured 6 coordinated actuated signalized intersections. The sample section of the corridor was about 2.4 miles, with the distance between intersections varying from 0.15 mile to 1.5 miles. Compared to the corridor in Site 2, Site 1 is considered to be less congested, with about 600 vehicles per hour per lane during peak hours. Data were collected over two days at an off peak period (1:30 pm to3:00 pm) and PM peak period (4:30 pm to 6:00 pm). The before study was conducted on 12/15/2008 when signals were still in actuated isolated control mode. The after study was conducted on 3/5/2009 after the coordinated actuated time plan had been implemented. Two vehicles were equipped with a GPS device to collect travel time data in both directions of the corridor. The vehicles started at the two end points of the corridor to collect data at the same time. Once each vehicle reached the end of the study corridor, they simply turned around and performed a run in the opposite direction. Site 2 was used to examine the impact of an adaptive split feature within the coordinated actuated signal system.

Traffic volume and stopped delay was also measured for both sites using Jamar® traffic counters and Sony® video cameras. Stopped delay was primarily collected by the video cameras. The video cameras were only used to collect volumes when the person operating the traffic counters could not cover all four intersection approaches because of high traffic volumes. Volumes were collected at Site 1 for both the before and after periods. The researchers successfully hypothesized that volumes would not significantly change from the pre to post-installation of the signal coordination. Additionally, travel times were improved by 30% to 34% after the signal coordination occurred. Exact times can be viewed in Table 2.2 shown below. Additionally, large improvements were made in stopped delays on coordinated approaches, while stopped delay actually increased by about 14% on the non-coordinated approach arterials that connect to the main study corridor. However, since the approach arterials carry lower traffic volume than the main study corridor and the objective of the signal coordination is to minimize total system delay, this increase is an expected necessary tradeoff. The research concludes that the coordinated actuated signal system outperforms the actuated isolated signal system by an average of 32% as measured by reduction in travel time through the corridor. The researchers recommended that VDOT traffic engineers should implement coordinated actuated traffic signal systems with the consequence that the coordination may increase delays in non-coordinated approaches off the main arterials. Additionally, even when signal spacing exceeds 0.75 mile (1.21 km), the researchers recommended that VDOT engineers should consider implementing signal coordination (Chen and Park 2010).

Table 2.2 Virginia Field Travel Time Comparison at Site 1 (Chen and Park 2010)

Gloucester County	Non-Coordinated Actuated System (Before)		Coordinated Actuated System (After)		Improvements (sec,%)	
	Average (sec)	STDEV	Average (sec)	STDEV		
Off Peak	663	63	465	28	198	30%
PM Peak	713	115	473	40	240	34%

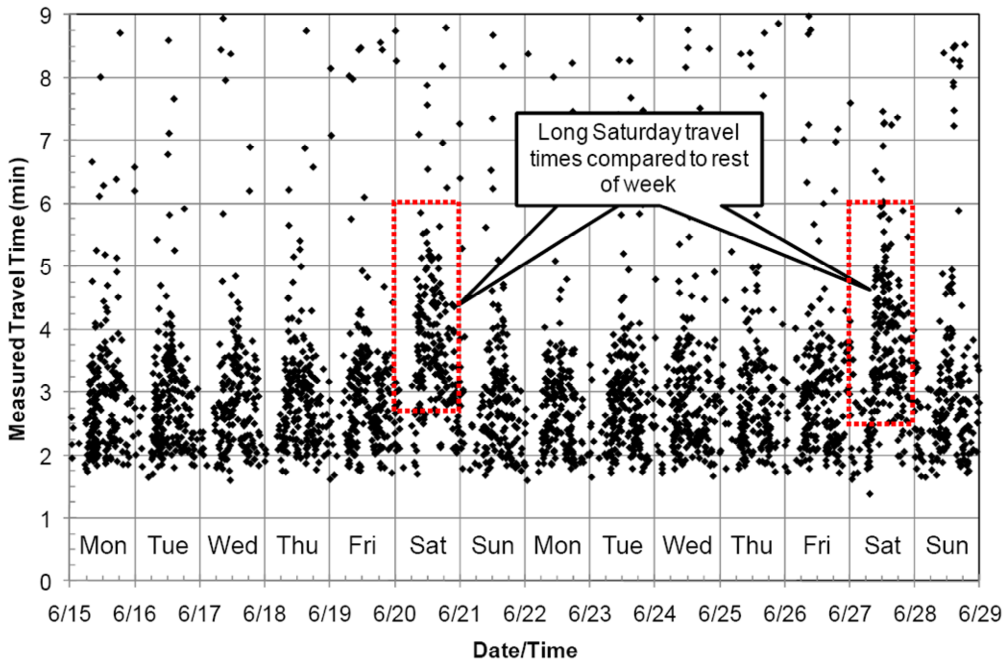
The Virginia Transportation Research Council also assembled a benefit-cost analysis (BCA) to evaluate implementing a coordinated actuated traffic signal system against a non-coordinated system from an economic standpoint. They assumed the value of travel time to be \$15.47 per hour (Schrank and Lomax 2009) and the cost of maintenance on the signal controllers to be \$200 and \$300 for non-coordinated and coordinated systems, respectively. The calculated travel time savings based on field data measurements during the PM peak hour was 9.94 vehicle hours per intersection. Table 2.3 shows the BCA calculations for both coordinated and non-coordinated movements at Site 1. The calculations yielded a savings in 2,982 vehicle-hours per intersection during the peak hour. This number correlates to savings of \$46,131.54 annually per intersection and \$374,026.30 over 10 years per intersection at a 5% annual interest rate (Chen and Park 2010).

Table 2.3 Benefit Cost Analysis Calculations for Signal Coordination at Site 1 (Chen and Park 2010)

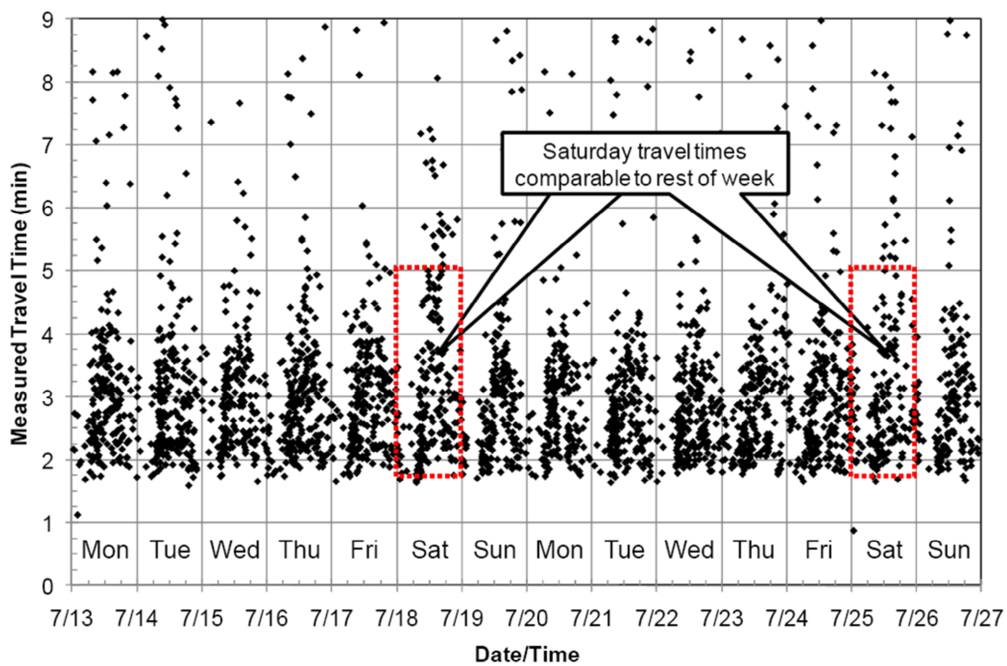
	Category	Base (non-coordinated)	Alternative (coordinated)
Cost	Annual traffic controller maintenance cost ($)	$200	$300
	NPV maintenance costs for 10 years ($) [note: net present value for 10 years annual maintenance costs]	$1621. 6	$2432.4
	Net costs for implementing coordinated signal system	$2432.4 – $1621. 6 = $810.8	
Benefits from coordinated movements	Peak hour volume for coordinated approaches (veh/hour)	2000	
	Corridor round trip travel time (sec/veh) (from Table 7)	713	473
	Travel time savings per coordinated movements vehicle at each intersection (sec/veh) [note: a corridor with five intersections has 6 links per direction]	(713 – 473) ÷ (6 links ×2 directions) = 20	
	Travel time savings per hour, coordinated movements per intersection (veh-hour)	2000 × 20 ÷ 3600 (sec/hr) = 11.11	
Benefits from non-coordinated movements	Peak hour volume for non-coordinated approaches (veh-hour)	700	
	Peak hour stopped delay at non-coordinated approaches (sec/veh) (weighted average from Table 6)	38.4	44.43
	Travel time saving per non-coordinated movements vehicle at each intersection (sec/veh)	–6.0	
	Travel time savings per hour, non-coordinated movements per intersection (veh-hour)	700 × (–6) ÷ 3600 (sec/hr) = –1.17	
Combined Benefits	Travel time savings per intersection (veh-hour)	11.11 + (–1.17) = 9.94	
	Annual total peak hour savings per intersection	9.94 × 300 weekdays = 2,982 hours	
	Annual peak hour savings ($)	2982 × 15.47 ($/hour) = $46,131.54	
	NPV Travel time savings over 10 years per intersection [note: net present value for 10 years annual savings]	$374,026.30	
B/C Analysis	Benefit cost ratio (net benefit / net costs)	$370,025.3 ÷ $810. 8 = 461.3	

2.3.1.2 Purdue University Study on Arterial Progression Quality

Purdue University also performed a study to assess the effectiveness of a signal coordination program, specifically introducing an offset tuning project (Day et al., 2010). The research introduces a vehicle re-identification technique using Bluetooth media access control (MAC) address matching. This field technique allowed researchers to compare the existing signal offsets' effectiveness against the effectiveness of the implemented offset coordination. Rather than using a floating car technique (i.e., one travel time measurement per run), the researchers decided to implement a vehicle re-identification technique, which produces a higher number of data points. A section of SR 37 in Noblesville, Indiana was selected as the study corridor because it contained an actuated coordinated system on its four signalized intersections. Passive test vehicles already in the traffic stream that happened to contain discoverable Bluetooth enabled devices were used as probe cars. Vehicles with such devices make up between 5% and 10% of the traffic stream. Four permanent and five temporary Bluetooth sensors were established at the intersections and midblock locations, respectively to track the passive test vehicles moving through the sample corridor. When a probe vehicle passes a sensor, the sensor records the MAC address of the discoverable Bluetooth device. Therefore, travel times can be obtained by capturing MAC addresses at multiple locations and calculating the time it took for the MAC address to travel from one sensor to the next. The large number of sensors allow for travel times to be computed for up to 17 different sections of the corridor, thus accounting for vehicles entering or exiting the corridor section. Travel times were collected over a two-week period for the before offset setting and for another two-week period for the after coordination offset settings. For both two-week periods, approximately 5,000 MAC addresses were acquired by the sensors. Figure 2.2 shows the results of the travel time study for vehicles travelling in the northbound direction with Saturday signal phasing being utilized.



(a) Before offset adjustment (N=4797)



(b) After offset adjustment (N=5401)

Figure 2.2 Travel times for Passive Test Vehicles Across the Sample Corridor (Day, Haseman et al. 2010)

2.3.1.3 *Evaluation of a Traffic Signal System by the Midwest Research Institute*

An evaluation of another traffic signal coordination was performed in Lee's Summit, Missouri by the Midwest Research Institute (Hutton, Bokenkroger et al. 2010). The study was performed on a 2.5 mile (4.0 km) section of MO 291 featuring 12 signalized intersections. Intersection spacing ranges from 250 ft (0.047 m) to nearly 3,000 ft (0.57 m). There were three separate data collection periods: a baseline case conducted in November 2008 to reflect the corridor before the introduction of a signal coordination, and two post-installation periods conducted one and five months after the installation (i.e., April 2009 and September 2009, respectively). Travel time runs, minor-street delay studies, traffic volume counts, and turning movement counts were all performed to evaluate the signal coordination.

Traffic volume counts were performed for both directions at three separate midblock locations on the corridor during each of the three study periods. Unicorn Traffic Classifiers and road tubes were used to collect 15-minute axle counts during the five time-of-day study periods. After collection, the volumes were summed across all sites for each time-of-day study period and analyzed to determine whether volumes were statistically significant based on the before-and-after scenario. The results indicated that there was no significant difference in before-and-after volumes. Therefore, any reductions in travel time, delay, or congestion were not because of any change in traffic volumes.

Travel time runs were conducted during five time periods (3 peak hour, 2 off-peak periods) over three weekdays (i.e., Tuesday, Wednesday, and Thursday) per week. The driver used the GPS test vehicle method to perform four vehicle runs in each direction for each time period. The GPS receiver, which was mounted to the roof of the vehicle, collected location stamps at 1-second intervals and calculated speeds for every location stamp. Drivers were instructed to drive with the flow of traffic. Initial tests concluded that there was no significant difference between the two post-installation data collection periods nor the day of the week the data was collected on. Therefore, this data could be pooled together, meaning a before-after analysis could be performed based on the installation of the signal coordination. Two-sample t-tests were used to compare the average travel times from the before and combined after data collection periods. The t-tests were run at 95% confidence levels and deemed statistically significant if p-values were less than 0.05. Table 2.4 and Table 2.5 show the changes in travel time for both the northbound and southbound directions, respectively.

Table 2.4 Before-and-after Travel Times in Northbound Direction (Hutton, Bokenkroger et al. 2010)

	Travel time (sec)				
Time Period	**Before**	**After**	**Difference**	**Standard error**	**P-value**
AM Peak	246	250	4	11.5	0.724
AM Off Peak	247	234	-13	8.4	0.13
Noon Peak	306	251	**-55**	12.6	**<.001**
PM Peak	292	248	**-44**	13.7	**0.003**
Night Off Peak	244	210	**-34**	6.6	**<.001**

Table 2.5 Before-and-after Travel Times in Southbound Direction (Hutton, Bokenkroger et al. 2010)

Time Period	Travel time (sec)				P-value
	Before	After	Difference	Standard error	
AM Peak	343	233	**-110**	10.7	**<.001**
AM Off Peak	370	226	**-144**	13.4	**<.001**
Noon Peak	392	245	**-147**	13.6	**<.001**
PM Peak	344	270	**-74**	17.5	**<.001**
Night Off Peak	251	232	**-19**	7.6	**0.019**

In the northbound direction, travel times decreased by 5% to 17% for all test periods except for the AM peak period, where travels times actually increased by 1.6% on the corridor after the coordination was implemented. The decreases in travel times for the noon peak, PM peak, and night off peak periods were all statistically significant (shown in boldface in on Table 2.4), with the greatest decrease of 17% occurring in the noon peak period. The lack of statistically significant reductions in travel times for the AM peak and AM off-peak periods was explained by the fact that the previous signal timing plan was set up to favor traffic from the northbound direction during morning hours. Therefore, the reduction in travel times were not as large as other scenarios. In the southbound direction, travel time reductions were greater than the travel time reductions in the northbound direction. This occurred because the travel times in the southbound direction for the before scenario were almost 100 seconds greater than those in the northbound direction. All five time periods encountered a statistically significant reduction in travel times for the southbound direction according to Table 2.5. Additionally, the researchers used the distance of the study corridor and its speed limit, 45 mph (72 km/hr), to create a hypothetical situation in both situations. Using this logic, they were able to create hypothetical travel times for situations with no delay due to congestion or signals and compare these hypothetical travel times to the collected before travel time data. Therefore, the theoretical delay due to traffic signals was calculated and used to evaluate which direction and time periods had the greatest opportunity for improvement before the coordination was implemented. For the southbound direction, the morning off peak and noon peak periods had the greatest opportunity for improvement, and thus both realized reductions in travel time approaching 40%, the greatest reductions for all time periods in either direction. The researchers concluded that the adaptive traffic signal system was successful in reducing travel times across both directions of the corridor from 7% to 39%.

In addition to travel time studies performed for an entire corridor, the Midwest Research Institute ran a series of other tests and analyses including: collecting the delay at each individual intersection, using the travel time data to calculate the number of stops along the corridor and the amount of congestion occurring along the corridor, simulating the fuel consumption and emission changes, and collecting minor-street delay. The average number of stops and the congestion amount were calculated using each vehicle's speed profile. The number of stops was defined by the amount of time each vehicle's speed fell to below 3 mph per run. The data was averaged for all runs for each time period in both directions. Once again, other than the northbound AM peak period, all times in the northbound and southbound directions experienced a decrease in the average number of stops by 69%. The average number of stops is a very noticeable measure of effectiveness for the general population because drivers generally use it to grade the quality of their trip. The average amount of time a vehicle spends in congestion was calculated in two different categories: (1) the amount of time a vehicle spent travelling at

20 mph or less (Mid-America Regional Council's definition of congested speed), and (2) the amount of time a vehicle spent travelling at 30 mph or less, which was chosen by the research team as a less congested speed amount. The results were as expected, with the southbound AM non-peak and noon peak seeing the most improvement after the signal coordination. The average speed in the southbound peak increased by approximately 15 mph (24 km/hr), or 60%, while the time spent in congestion decreased by over 90%. The AM peak period in the northbound direction showed an increase of 22.1% in the average amount of time each vehicle spent in congestion (i.e., < 20 mph), corresponding to the increased travel time after signal coordination (Hutton, Bokenkroger et al. 2010).

2.3.1.4 Evaluation of a Traffic Signal Coordination Across Jurisdictional Boundaries

In a study performed in Arizona, Rakha et al. used GPS-equipped vehicles to measure the second-by-second speeds along a corridor that crosses jurisdictional boundaries into two separate cities (2000). The overall objective of the study was to evaluate the before-and-after improvements of a signal coordination along a 6 mile (9.7 km) section of roadway that runs from the Scottsdale to Tempe. The section of roadway was one of the busiest corridors in the Phoenix metropolitan area, running straight through Arizona State University to the south, and downtown Scottsdale to the north. The study section also contained a railroad crossing. Problems occur because the two jurisdictions cannot operate the traffic signals at a common cycle length because of confounding factors (i.e., different signal operating systems and lack of interoperability between the two municipalities). Therefore, in an attempt to shift from the less efficient city boundaries to a functional boundary, a change was made in the cycle lengths at three intersections in between the two jurisdictions. This change meant that all 21 traffic signals on the corridor were working together, with the 16 in Tempe coordinated with the 5 in Scottsdale. To quantify the benefits, the evaluation effort consisted of a field volume study using midblock tube counts, intersection turning movement counts, and a travel time study using GPS equipped test vehicles. The second-by-second GPS data was used to evaluate the efficiency, energy, environmental, and safety impacts of operational level traffic improvement projects. The data was collected over a one month period from January to February of 1999. Midweek collection periods (Tuesday through Thursday) were used to reflect typical weekday traffic conditions. Three GPS-equipped probe vehicles were driven along the sample corridor during the a.m. peak (7:00 to 9:00 a.m.), midday peak (11:00 a.m. to 1:00 p.m.), and p.m. peak (4:00 to 6:00 p.m.) period. Latitude, longitude, direction heading, and speed were measured every second by the GPS unit. These measurements were not corrected because they had no bearing on the accuracy of the speed measurements. A total of 301 runs (141 before condition runs, 160 after-condition runs) were conducted from one end of the corridor to the other (Rakha, Medina et al. 2000).

The traffic volume counts were performed by installing traffic tube counters at six midblock locations on the corridor. The counters collected 15 minute traffic volumes over the course of three days. The results initially showed that Arizona State was a major trip generator for the corridor. To analyze the results, ANOVA tests were performed to show whether volumes significantly changed based on the approach direction and the before-and-after conditions. The counts for the approach directions (northbound and southbound) were statistically different as hypothesized; however, there was no statistical difference in traffic volumes for the before and after conditions. This lack of a statistical difference between the counts indicate that the signal coordination did not induce more traffic or demand.

After collecting the GPS data for both the before and after scenarios, ANOVA tests were used to analyze the data according to three factors: before-and-after scenario, analysis period (a.m. peak, midday, or p.m. peak), and direction (northbound or southbound). The ANOVA tests used the test vehicles' average speed profiles to determine whether the factors were statistically significant. The average speed profiles along with 95% confidence intervals were used to perform ANOVA tests at the 5% level of significance. Some of the results included:

- The difference in speed between the before and the after scenarios was statistically significant (p =0.0001).
- The number of vehicle stops was reduced by 3.6%, from average of 7.2 to 6.9 stops/trip, which was found to be a marginally statistically insignificant change (p = 0.0615).
- During the a.m. peak period, the average speed increased from 28.2 to 29.8 mph (45.4 to 47.9 km/h) in the northbound direction and increased from 29.5 to 30.0 mph (47.5 to 48.2 km/h). This increase was found to be marginally statistically significant (p = 0.046).
- The ANOVA results for the midday were not statistically significant for average speed. The average speed increased from 27.0 to 28.6 mph (43.5 to 46.0 km/h) in the

northbound direction and decreased from 29.1 to 28.2 mph (46.9 to 45.4 km/h) in the southbound direction.

- Mixed results occurred in the p.m. peak period ANOVA testing based on the direction of vehicle traffic. Specifically, while the northbound results increased insignificantly from 38.5 to 41.1 km/h (23.9 to 25.5 mph), the southbound results significantly increased from 29.5 to 38.7 km/h (18.3 to 24.0 mph) (Rakha, Medina et al. 2000).

Again, a summary of the signal coordination literature is shown in Table 2.6**.** Unlike in Table 2.1, most of the studies in the signal coordination table have similar purposes. The type of analysis column was also used in developing the architecture for evaluating speed, volume, and travel time along Donahue Drive. Additionally, the conclusions section indicates how effective each of the reviewed studies were in evaluating the signal coordination. A combination of the parameters of each study were used in developing the architecture for evaluating the signal coordination and the overall study.

Table 2.6 Summary of Signal Coordination Case Studies from the Literature Review

Studies / Locations	Purpose of Study	Type of Data Collection	Types of Analysis	Conclusions
(Chen and Park 2010)/ Gloucester County, VA	To quantify the benefits of signal coordination on two corridors with varying congestion levels	• Travel time collection using two vehicles to perform the GPS test vehicle technique • Traffic volume was collected using both traffic counters and video cameras • Stopped delay was collected using the same video cameras	• Comparative analysis was performed on the before-and-after travel times and traffic volumes • Additionally, the field data was compared with a Synchro model to predict congestion. • A Benefit-cost analysis was performed to quantify the benefits of a coordination in dollars.	• The coordinated system outperformed the isolated system to the point that researchers recommend that coordination is effective when signal spacing exceeds 0.75 mile • The BCA concluded that over $45,000 per intersection could be saved with coordination.
(Day, Haseman et al. 2010) /Noblesville, IN	To assess the effectiveness of a new signal offset system against the existing offsets	• Travel time collection using a vehicle re-identification technique with MAC addresses.	• Researchers were able to collect averaged travel times for 17 sections of the sample corridor.	• The new offset generally outperformed the existing system, with average travel times reducing. However, no analysis was reported to measure the significance of the reductions.
(Hutton, Bokenkroger et al. 2010) / Lee's Summit, Missouri	To evaluate a new adaptive traffic signal system at different time periods after implementation using several different measurements	• Travel time collection using the GPS test vehicle technique. • Traffic volume was collected using traffic counters and pneumatic tubes at three locations. • Minor street delays were performed on four streets according to the HCM. • Turning movement counts were collected manually and by traffic cameras.	• T-tests were performed to compare before-and-after travel time data, deeming whether significant changes occurred. • Before-and-after volumes were compared to ensure that reductions in travel time were not the result of changes in traffic volume through the corridor. • Travel time data was used to calculate intersection delay, average number of stops, and simulate fuel consumption.	• Travel times were significantly reduced in both directions of the corridor • Both post-coordination travel time collections were combined into one because there were no significant differences after a T-test • The time periods with that experienced the greatest delay due to signals before the coordination experienced the greatest reductions in travel time after the coordination
(Rakha, Medina et al. 2000)/ Scottsdale, AZ and Tempe,AZ	To evaluate the benefits of a signal coordination performed across jurisdictional boundaries	• Travel time collection using the GPS test vehicle technique • Traffic volume using midblock tube counts • Intersection turning movement counts	• ANOVA tests were run to determine whether volume significantly changed after the coordination and whether direction was significant. • ANOVA tests were also used to determine whether the test vehicles' speed profiles were significantly different according to direction, time of day, and before or after scenario.	• The differences in travel times and speed between the before and after scenario were significant • Direction and time of day differences varied from marginally statistically significant to not significant.

Using the various techniques and methods adopted from a variety of the reviewed literature, an architecture was developed to evaluate the effects of various improvements including a traffic signal coordination down the corridor. Methods from the literature described in both Table 2.1 and Table 2.6 were selected in developing the data collection and analysis framework. The most efficient and plausible methods for collecting and evaluating traffic data across a signalized campus arterial were selected to makeup the framework discussed in Chapter 3. Additionally, the reasoning behind the selection of each data collection and analyses method is discussed in detail in Chapter 3.

Chapter Three: Data Collection and Analysis Procedures

3.1 Introduction

Upon reviewing the aforementioned research, a variety of methods exist to evaluate the effectiveness of traffic signal improvements made along a corridor. The research presented herein addresses the practices selected to evaluate the benefits/effects of the following improvements made on a campus arterial: (1) the installation of two new traffic signals and (2) the implementation of a 7 signal coordination. This chapter is divided into two sections: (1) the selection of data collection materials and methods, and (2) a description of methods used to analyze the collected data, and the procedures for statistical analyses. The data collection section includes the methods for measuring traffic volumes, vehicle mean speeds, and the average travel time measured along the corridor during the peak periods. The analyses section includes the methods for processing the raw data into usable data for analysis. It also addresses the types of statistical tests conducted on the data for evaluating the significance, or lack of significance, pertaining to any reductions or improvements within the traffic system along the corridor. The processed data and the results of the analyses conducted are included in Chapter 4: Experimental Analysis results and discussion.

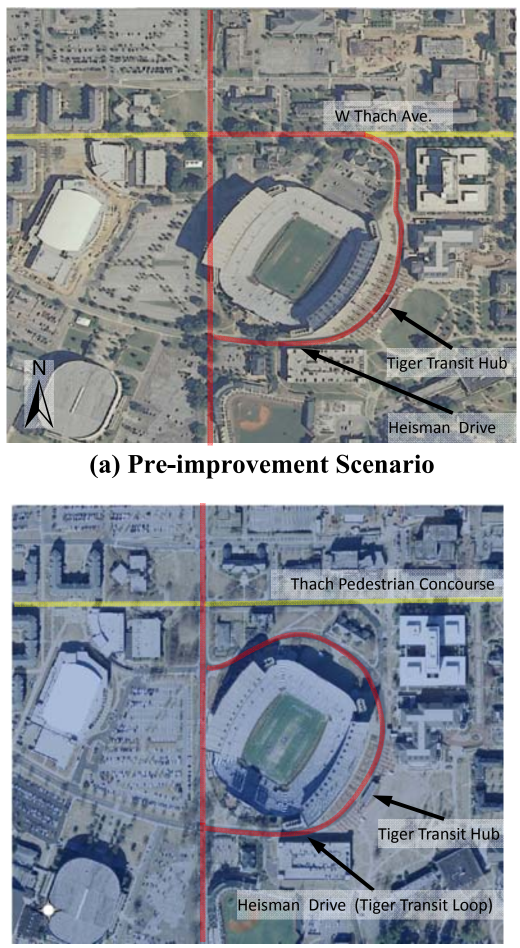
3.2 Data Collection Using Field Studies

Two main field studies were conducted in attempt to quantify and assess the changes made on S. Donahue Drive. Pneumatic traffic counters were used to collect traffic volume and mean vehicle speeds over the course of a work week for both the before and after improvement scenarios. Sample average travel times were measured using the GPS test vehicle method.

3.2.1 Field Data Collection Study Period

Selection for the time elements of the field study were made using the time elements mentioned in FDOT's guidelines for collecting travel times using GPS technology (Ngo-Quoc, Kwan et al. 2004). For the pre-improvement scenario, the week of March 29 through April 2, 2010 was selected to represent an average traffic week on the corridor. Auburn University was in the 9^{th} week of its spring semester with a full week of classes scheduled. Data were collected Monday-Friday. It is important to note that a crossing guard was employed by the university to direct traffic at the intersection of S. Donahue Drive and W. Thach Avenue. The intersection was controlled under the authority of the crossing guard from 7:30 a.m. to 5:00 p.m, but operated as a three-way stop at other times. The crossing guard facilitated crossing over S. Donahue Drive for students entering or exiting campus as well as giving Tiger Transit buses departing from W. Thach Avenue priority when turning onto S. Donahue Drive. Additionally, congestion along S. Donahue Drive was mitigated while the crossing guard was in place at the intersection, easing the flow of traffic along the corridor.

As previously mentioned, since two sets of corridor improvements were installed over the course of a year, three separate data collection periods were performed to evaluate the piecewise improvements. Phase I Intermediate Improvement data collection occurred during the first two weeks in April of 2011. This data collection sequence was designed to quantify and assess any intermediate improvements, made by the conversion of W. Thach Avenue into a pedestrian only concourse and the opening of the N. Heisman Drive intersection. The changes to the Tiger Transit Loop from the pre-improvement data collection period to the intermediate improvement period are shown by Figure 3.1.



(a) Pre-improvement Scenario

(b) Intermediate Improvement Scenario

Figure 3.1 Tiger Transit Loop Changes Across Data Collection Periods

Note: Yellow Streets are pedestrian-only.

Notice how W Thach Ave. formerly served vehicles departing the Tiger Transit hub from Heisman Drive. Once the Heisman Drive loop was completed, W Thach Ave. was permanently converted to a pedestrian-only street.

Figure 3.2 shows the changes in traffic and pedestrian framework made to the intersection of Donahue and W Thach Avenue across improvement periods. The two pedestrian crosswalks shown in the pre-improvement scenario (i.e., Figure 3.2(a)) were deleted, and replaced with a central speed table with a raised pedestrian crosswalk in the intermediate improvement scenario (i.e., Figure 3.2(b)) to reduce vehicle speeds.

(a)Pre-Improvement Scenario

(b) Intermediate Improvement Scenario

Figure 3.2 W Thach Avenue Intersection Changes Across Data Collection Periods

Additionally, the university relocated the crossing guard to the newly formed N. Heisman Drive Intersection, shown by Figure 3.3, during the Intermediate Improvement Period. The crossing guard was only on-duty during campus hours (i.e., from 7:30 a.m. to 5:30 p.m). Since this intersection was a 3-way stop sign controlled intersection, the crossing guard took precedence over the stop signs, allowing increased traffic flow while also giving transit buses priority when turning onto S. Donahue Drive. Again data were collected Monday-Friday, April 4 through April 8, 2011.

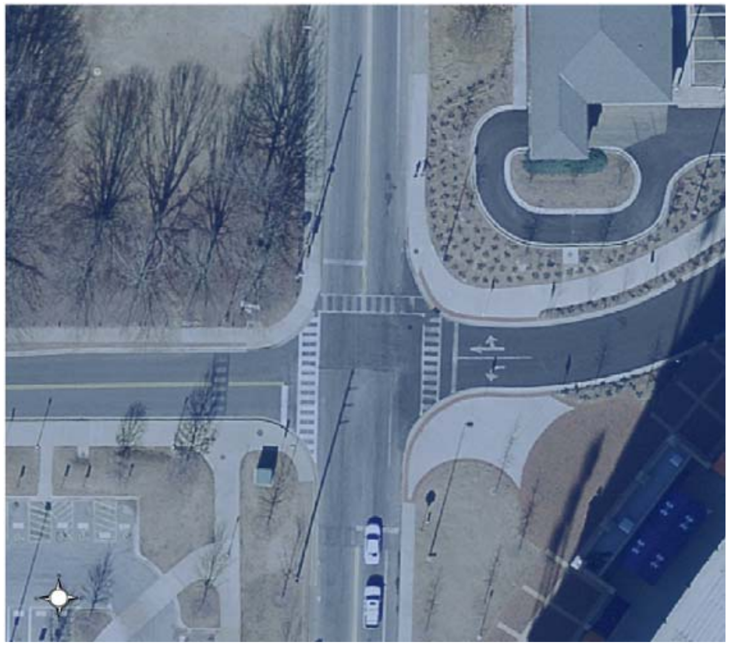


Figure 3.3 Newly Formed N. Heisman Drive Intersection

The final series of improvements, Phase 2 improvements, consisted of the installation of two new traffic signals, as well as the coordination of the signals at every intersection. These improvements were completed during December of 2011. Because of delays to the construction project schedule, data collection did not occur for the Phase 2 Improvements in a timely enough manner to be included in this study.

For travel time collection, three peak traffic periods (i.e., morning, noon, and evening) were selected to show how the corridor performs during highly congested periods. The morning peak period of 7:30 a.m. to 9:30 a.m. was used to coincide with the beginning of classes on campus. The evening peak period was estimated to be from 4:30 p.m. to 6:30 p.m. It should be noted that a crossing guard was employed to direct traffic and pedestrians at the W Thach Intersection during official university hours from 7:30 a.m. to 5:00 p.m. Moreover, a lunch time peak period was selected between 11:30 a.m.

and 1:30 p.m. This peak hour was selected because a large amount of students are typically departing and arriving on-campus around noon.

3.2.2 Traffic Volume Collection

In order to reach any significant conclusions about reducing congestion and improving traffic flow, traffic volumes for the three data collection phases needed to be collected. If traffic volumes were significantly different across any of the three data collection phases, no conclusions could be drawn about the signal coordination or the other changes made to the corridor. Therefore, traffic volume collection was deemed essential. Because several other major corridors intersect with the study section of Donahue Drive, it was also necessary to collect volumes at different locations on the study corridor. These different locations allowed for the volumes of vehicles entering and exiting the corridor at the major side streets and parking lots to be evaluated. Auburn University is one of the largest trip generators for vehicles accessing the corridor. Therefore, students and faculty can enter or exit the study section of the corridor at a variety of locations. Four midblock locations were selected for the counters to be installed. The locations are shown in Figure 3.4.

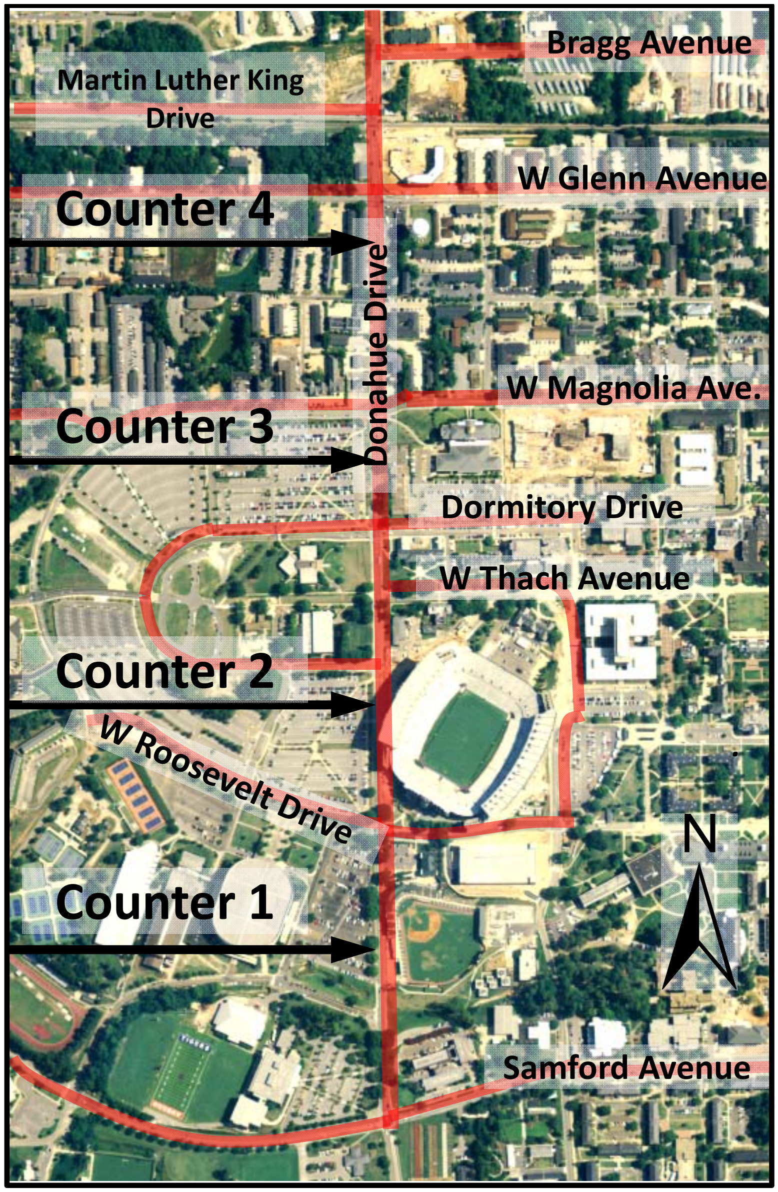
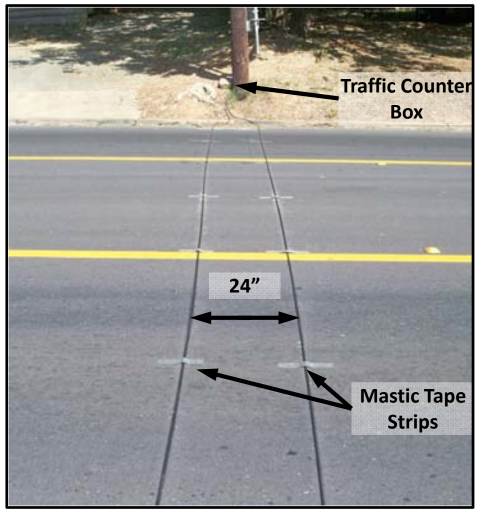


Figure 3.4 Traffic Counter Locations

The counter locations were selected to capture all traffic entering and exiting the study corridor as well as to capture the free flow speeds of the vehicles. For example, if a vehicle is traveling northbound through the corridor and turns on Roosevelt Drive, it will only be counted by counter 1. Therefore, the net amount of vehicles that enter and exit the corridor can be calculated. Additionally, by selecting midblock locations, vehicles are able to accelerate to free flow speeds before having to decelerate because of an upcoming intersection.

3.2.2.1 Traffic Counter Setup

Jamar Trax Apollyon traffic counters, shown in Figure 3.5(a) – (f), were used at the four selected locations because of their ability to record traffic volumes, vehicle speeds, and vehicle classifications. Prior to data collection, each counter was tested using Jamar's Traffic Counter Tester to ensure it was accurately recording data prior to installation. The installation of each traffic counter occurred one day prior to the data collection period. Two 50 ft pneumatic tubes spaced 24 inches apart were placed perpendicularly across the roadway at each of the four locations as seen in Figure 3.5(a). Each end was attached to a clamping device anchored down by a PK nail which was driven into the asphalt as shown in Figure 3.5(d). This device ensured that the tubes were as straight as possible but without creating too much tension. Strips of mastic tape were also used to secure the tubes to the asphalt. Each tube end that were on the opposite side of the road from the traffic counter was tied into a knot and secured to the pavement with mastic tape. The ends of the tubes on the corresponding side of the road were connected to the corresponding ports in the back of the counter to give the correct tube layout as illustrated in Figure 3.5(e). The counters were set to collect volume, speed, vehicle classification, and gap for the entire data collection period. Nearby light posts or trees were used to secure each counters using chains and locks. The counter boxes were also locked to discourage pedestrians from tampering with the setups. Figure 3.6 illustrates the four counter and tube setups. Collection began at 12:00 a.m. CST on Monday, March 29, 2010 and ran through 11:59 p.m. on Friday, April 2, 2010. All counters and tube setups were manually checked twice a day during the week to ensure accuracy. No rain events occurred during the week.



(a) Sample Pneumatic Tube Layout

(b) Trax Apollyon Traffic Counter

(c) Jamar Traffic Counter Tester

(d) Clamping Device and Nail

(e) Pneumatic Tube Connection

Figure 3.5 Traffic Counter Setup Details

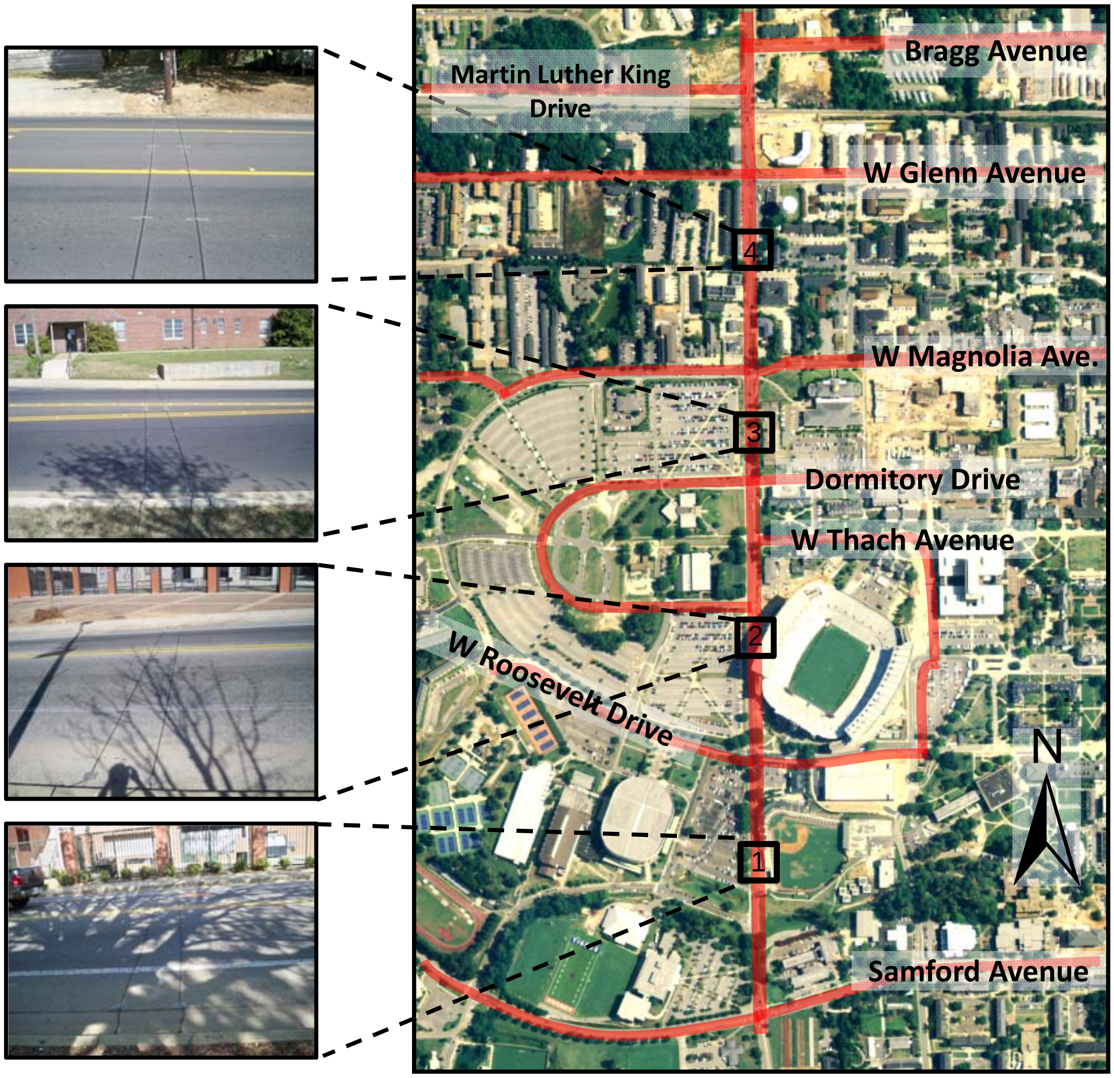


Figure 3.6 Traffic Counter Setup with Locations

Note: All photos were taken on the western side of Donahue Drive facing east.

3.2.3 Travel Time Collection

As previously stated, travel time collection was performed using the GPS test vehicle technique. For all three data collection phases, a custom GPS tracking device developed by DPS Engineering Inc. was attached to the test vehicle. The vehicle was driven northbound and southbound along the sample corridor as the GPS device collected position (degrees latitude and longitude) and speed (in mph) every second. The vehicle started at the northernmost intersection, Bragg Avenue, before driving to the southernmost intersection, Samford Avenue, to complete the first southbound run. After completely passing the southernmost intersection, the GPS device was turned off as the vehicle turned around. The device was then switched back on as the vehicle drove back northbound through the southernmost intersection until it reached the northernmost intersection. The GPS device was turned on and off after completing each run so that the GPS device would produce separate data files for each run. Having a separate data file for each run facilitated the data processing sequence before data analyses were carried out. To obtain statistically relevant travel times, Figure 3.7, taken from the *Florida Guidelines for Collecting and Analyzing Travel Time Studies* was used to determine that six runs in each direction would be sufficient for each peak period to achieve a ±3.0 mph permitted error recommended for arterials (Ngo-Quoc et al., 2005).

This procedure is represented by the following equation:

$$R = \frac{S}{N-1}$$

Example:

APPROXIMATE MINIMUM SAMPLE SIZE REQUIREMENTS FOR TRAVEL TIME AND DELAY STUDIES WITH CONFIDENCE LEVEL OF 95.0 PERCENT					
Average Range in Running Speed (mph)* R	Minimum Number of Runs for Specified Permitted Error				
	± 1.0 mph	± 2.0 mph	± 3.0 mph	± 4.0 mph	± 5.0 mph
2.5	4	2	2	2	2
5.0	8	4	3	2	2
10.0	21	8	5	4	3
15.0	38	14	8	6	5
20.0	59	21	12	8	6
*Interpolation should be used when R is other than the numbers shown in column 1.					

Run #	RS	Absolute Difference
1	38	0
2	35	3
3	32	3
4	33	1
5	36	3
		10 (Total = S)

$$R = \frac{S}{(n-1)} = \frac{10}{(5-1)} = 2.5$$

where

RS = average running speed in mph
R = average range in running speed in mph
S = sum of absolute differences
N = number of completed test runs

Figure 3.7 Procedures for Determining the Amount of Vehicle Runs per Collection Period (Ngo-Quoc et al., 2005)

The vehicle carried out this process 6 times in each direction for each peak period (a.m., midday, and p.m.). For each data collection phase, 5 days of weekday data were collected for all three peak periods resulting in a total of 180 total runs per data collection phase. A total of 540 GPS test runs were collected over all three data collection phases (i.e., Pre-improvement, Phase 1: Intermediate Improvement, and Phase 2: Final Improvement).

3.3 Data Processing and Analysis Procedures

Prior to analyzing both sets of field-collected data, both sets of raw data must be processed into usable datasets. Volumes must be processed and calculated before the speed and travel time data can be deemed effective. If traffic volumes are significantly different across the three data collection periods, the changes in speed and travel time because of the corridor improvements would be more indistinguishable to differentiate because of changes in demand. Therefore, volumes were processed and analyzed before speed and travel time data.

3.3.1 Traffic Volume Datasets

Vehicular volumes were processed and analyzed in a manual fashion using computer software. The methods for processing and analysis are based on the literature from other studies while also incorporating new ideas to optimize the data reduction process. The main objective of the processing and analysis of the observed volumes was to identify significant mean differences across any of the three data collection phases.

3.3.1.1 Traffic Volume Processing

Both speed and volume were collected using four Trax Apollyons. The data was transferred into Jamar's software suite TraxPro using a flash drive. As previously stated in Section 3.2.2.1, the counters collected speed and volume continuously over the course of a week. However, for each of the three data collection periods, only data from the three peak periods for each of the 5 weekday test period was used. Volumes were assembled into 8, 15-minute blocks per each time of day. The morning peak period was taken from 7:30 a.m. to 9:30 a.m., the midday peak period was taken from 11:30 a.m. to 1:30 p.m., and the evening peak period was taken from 4:30 p.m. to 6:30 p.m. The peak periods were selected to mirror those times used for travel time collection. Since travel time collection ranged from 1 to 2 hours, a two hour volume collection window (8 15-minute blocks) was used to evaluate the peak periods. Therefore, significant changes in volume across the three data collection periods (i.e., pre-improvements, intermediate improvements, and final improvements) could be identified. To better organize the volume blocks, an indexing system shown in Figure 3.8 was created to identify each volume. Thus, volume shown in the table corresponds to Monday, from 7:30 a.m. – 7:45 a.m. of the pre-improvement collection period. Any significant changes in volumes may correspond to changes in travel times across the collection periods, thus making the evaluation of the effects of the traffic and pedestrian improvements more difficult.

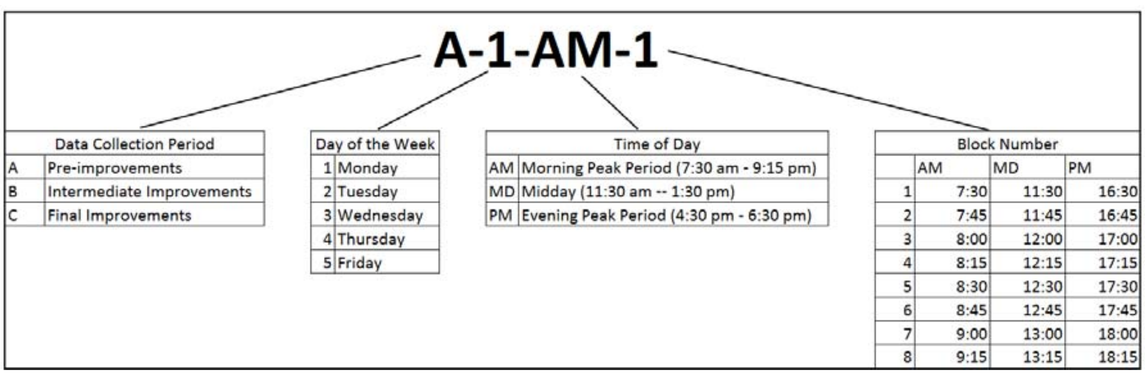


Figure 3.8 Volume Indexing Assembly

3.3.1.2 Volume Analysis

Analysis for comparing the traffic volumes was performed by using a series of T-tests. Since each improvement period had the same amount of collection days and the same peak periods, the paired t-test was deemed the most effective means for analyzing whether volumes had significantly changed across the improvement periods. Thus, for pairing the data together, all the subcategories of volume data (e.g. day of the week, peak period, 15-minute block number) were held constant and only the improvement period was changed. For example, the volume A-1-AM-1 was paired with B-1-AM-1 and C-1-AM-1, the same block volumes from the intermediate and final improvement periods. This method was adopted to correctly compare the improvements by ensuring that volumes did not significantly change across the data collection period without influence from other factors such as time of day or day of the week. The analysis was performed using paired t-tests at a significance level of α = 0.05 in SAS® Version 9.1.3. The null hypothesis, that travel time will significantly change, and alternative hypothesis, that no significant change will occur, are stated as follows:

$$H_0 : \mu_{A(ijkl)} - \mu_{B(ijkl)} = 0 \begin{cases} i = 1, 2, \ldots, n \\ j = 1, 2, \ldots, n \\ k = AM, MD, PM \\ l = 1, 2, \ldots, n \end{cases} \tag{1}$$

$$H_a : \mu_{A(ijkl)} - \mu_{B(ijkl)} \neq 0 \begin{cases} i = 1, 2, \ldots, n \\ j = 1, 2, \ldots, n \\ k = AM, MD, PM \\ l = 1, 2, \ldots, n \end{cases} \tag{2}$$

Where:

H_0 = null hypothesis

H_a = alternative hypothesis

μ_A= mean volume block collected during the after period

μ_B = the mean volume collected during the before period

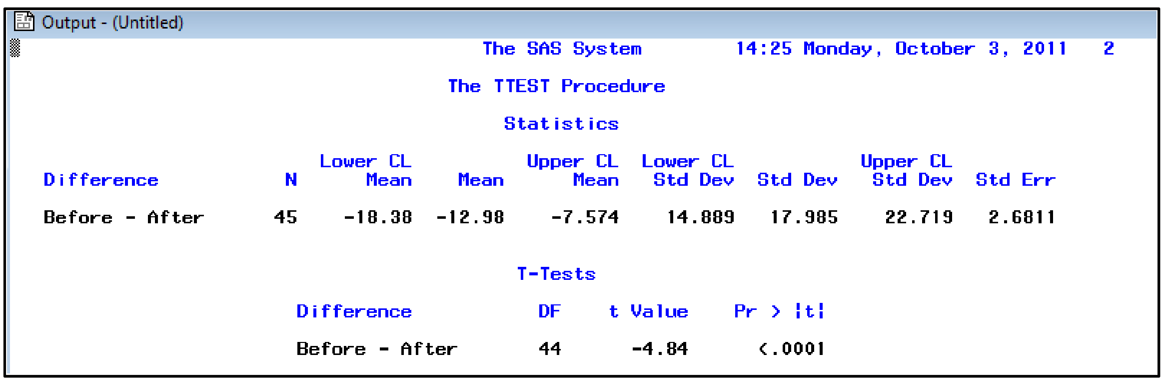
i = station number (n = 4)

j = day (n = 5)

k = peak period (AM, MD, PM, n = 3)

l = time block (n = 8)

Therefore, analysis only occurs on a single set of differences taken on the indexed paired volume dataset. A total of 24 datasets (12 northbound | 12 southbound) were sorted into 6 six SAS programs. These SAS codes can be seen in Appendix B. Each program resulted in 3 outputs containing a p-value for each paired dataset. A sample output can be seen in Figure 3.9. Statistically significant differences in volumes across collection periods were determined through p-values. If p-values were less than 0.05, changes in volume were assumed to be statistically different across collection periods. However, when p-values were larger than 0.05, changes in volume were concluded to be statistically similar.



Output - (Untitled)

The SAS System 14:25 Monday, October 3, 2011 2

The TTEST Procedure

Statistics

Difference	N	Lower CL Mean	Mean	Upper CL Mean	Lower CL Std Dev	Std Dev	Upper CL Std Dev	Std Err
Before - After	45	-18.38	-12.98	-7.574	14.889	17.985	22.719	2.6811

T-Tests

Difference	DF	t Value	Pr > |t|
Before - After	44	-4.84	<.0001

Figure 3.9 Sample SAS output

3.3.2 Speed Dataset

The speed dataset was designed to give supplemental information to the travel time study results while also demonstrating any increase or decrease in pedestrian safety. Large increases in speed could possibly have an adverse effect on pedestrian safety since S. Donahue Drive serves as the western boundary of the campus core for students and faculty traveling by foot, bicycle, and transit bus, in addition to personal vehicle. Both processing and analysis of speed data were more of a manual process than the volume or travel time studies.

3.3.2.1 Speed Processing

As previously stated, speed data was collected in mph using the four traffic counters. The processing was carried out again using Jamar's TraxPro software. The raw data was transported from the counter into the software using a flash drive. The raw data at each counter was processed using the Virginia DOT vehicle classification system. Unclassified vehicle (Class 14) pulses were discarded because they give a 0 mph speed reading that would distort speed calculations for each peak period. The raw data was converted into an Excel spreadsheet with the vehicle number, speed (mph), time, lane (direction), class, axle length (in), and gap (seconds) listed for every pulse. Each counter's raw data file was broken down by day and further by peak period. The same two hour windows; 7:30 a.m. to 9:30 a.m., 11:30 a.m. to 1:30 p.m., and 4:30 p.m. to 6:30 p.m., were used as the AM, midday, and PM peak periods from the volume analysis. However, for simplification purposes, descriptive statistics were only run for the entire two hour windows rather than separating the peak periods into 8, 15-minute blocks. Descriptive statistics gave a mean, median, mode, variance, standard deviation, and a count (volume). Additionally, an 85th percentile speed was estimated by adding the mean speed to the standard deviation.

3.3.2.2 Speed Analysis

Speed analysis was performed using the mean speed calculations as well as the standard deviations. Again, parameters were kept consistent so that the different improvement periods were isolated for comparison. A series of twelve, two –sample t-tests were run for each direction (24 total). The null hypothesis and alternative hypothesis are stated as follows in Equations 3 and 4:

$$H_0 : \mu_{A(ij)} = \mu_{B(ij)} \tag{3}$$

$$H_a : \mu_{A(ij)} \neq \mu_{B(ij)} \tag{4}$$

Where:

H_0 = null hypothesis

H_a = alternative hypothesis

μ_A= mean speed collected during the after period

μ_B = the mean speed collected during the before period

i = station number (n = 4)

j = peak period (AM, MD, PM)

The test statistic, or t-value used in the t-test for speed analysis is as follows:

$$t = \frac{\mu_A - \mu_B}{S_p\sqrt{1/n_B + 1/n_A}} \tag{5}$$

Where:

t = test statistic for speed significance

μ_A= mean speed collected during the after period

μ_B = the mean speed collected during the before period

S_p = pooled standard deviation

n_B = number of speed observations collected during the before period

n_A = number of speed observations collected during the after period

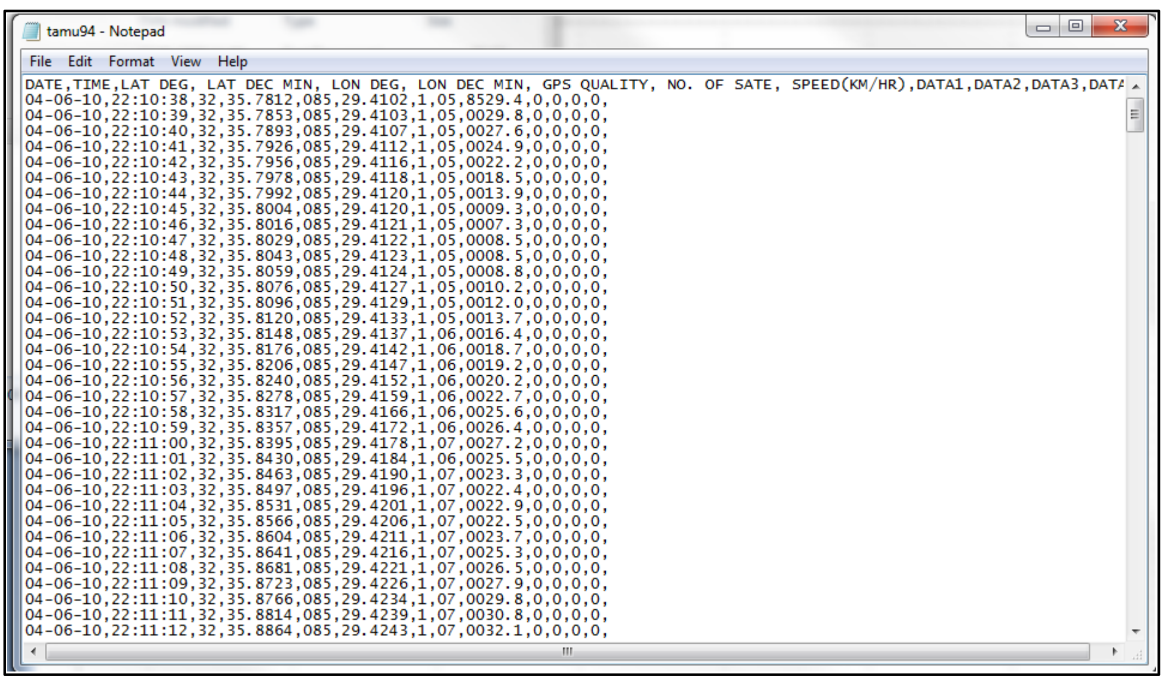
SAS® was used to run the tests, and again the p-value was used to determine whether a statistically significant change in mean speed occurred across improvement periods with a selected level of significance of 0.05.

3.3.3 Travel Time Dataset

Since travel time is perhaps the most noteworthy indicator for general users of the roadway, it is featured in this study as the most significant measure of evaluating the overall effects of the roadway improvements. The largest portion of this study's resources was dedicated to creating and carrying out this portion of the research. Most of the processing and analysis methods were developed from previous literature and optimized to satisfy the overall objectives of this study

3.3.3.1 Travel Time Processing

Travel time processing began by importing the raw data from the memory card that was written by the GPS device to a computer. As previously stated, the GPS device wrote a comma delimited text file for each travel time run to the memory card. An example text file can be seen in Figure 3.10.


tamu94 - Notepad

File Edit Format View Help

```
DATE,TIME,LAT DEG, LAT DEC MIN, LON DEG, LON DEC MIN, GPS QUALITY, NO. OF SATE, SPEED(KM/HR),DATA1,DATA2,DATA3,DATA
04-06-10,22:10:38,32,35.7812,085,29.4102,1,05,8529.4,0,0,0,0,
04-06-10,22:10:39,32,35.7853,085,29.4103,1,05,0029.8,0,0,0,0,
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04-06-10,22:11:03,32,35.8497,085,29.4196,1,07,0022.4,0,0,0,0,
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04-06-10,22:11:12,32,35.8864,085,29.4243,1,07,0032.1,0,0,0,0,
```

Figure 3.10 Sample Travel Time Text File

Microsoft Excel was used to convert the text files into spreadsheets. Once in spreadsheet form, the columns for latitude degrees and decimal minutes were aggregated into a single latitude decimal degree column. Since S. Donahue Drive runs almost completely north and south, longitude did not vary more than 0.0003 degrees at any point in any of the runs and was therefore discarded. Additionally, speed was converted from kilometers per hour measured on the GPS device to mph to comply with all other speed measurements in this study.

Similar to the studies performed by Hunter et al. and Billings et al. previously mentioned in Chapter 2 of this thesis, reference lines were used to further categorize travel times recorded in the study (Hunter, Seung et al. 2006) (Billings and Jiann-Shiou 2006). To isolate different intersections and provide link travel times, the sample corridor was broken into four sections by a series of reference lines, shown in Figure 3.11. Rather than make the sections equal lengths, 6 critical intersections were chosen to separate the link travel time sections. The intersections chosen were, from north to south, were the Bragg Avenue Intersection, Magnolia Avenue Intersection, Thach Concourse Intersection, S Heisman Drive Intersection, and the Samford Avenue Intersection. These intersections serve as the boundaries to the four roadway sections. The intersections were chosen so that the traffic counter locations would be approximately halfway between them. This location allowed for comparisons to be made between the travel time study and the speed and volume studies. Additionally, the selected intersection locations for the travel time study would be a key indicator used to evaluate the effectiveness of the traffic signal coordination. This intersection is the southern boundary of the sample section of Donahue, and therefore the southernmost point of the intersection must be used to incorporate in the effects of the signal at that intersection. Several of the travel time datasets (runs) were imported into ArcGIS as object files using ArcCatalog. The data from these runs were overlaid onto an aerial photo of the sample section as a layer. ArcGIS stored all of the information provided by the spreadsheet into an attribute table when the file was imported. Therefore, using the symbology function, each data point was able to be colored based on the speed being traveled when the position stamp was made. The positions of the vehicle, taken at 1 second intervals, are shown in Figure 3.11 by the colored circles, which have been enlarged for visual purposes. The colors of the circles indicate the speed that the vehicle was traveling at each second. These colors were used to examine where the test vehicle spent waiting in queue for the signal to turn and where it accelerated to free flow speed. Reference lines were drawn at points where the vehicle began to accelerate through the critical intersections using the ArcGIS file. Therefore, there was a traffic signal at the end of each section regardless of which direction the vehicle was travelling except for the Thach Pedestrian Intersection, which was not a signalized intersection until the final improvements phase. Any time spent in queue as a result of a red signal was spent at the end of a section. Once the vehicle crossed the threshold of the intersection, it crossed the reference line indicating it was in a new section of the study corridor. The latitude coordinates of the carefully draw reference lines were recorded and used in the actual travel time calculations.

Travel time calculations for each run were actually performed using a Visual Basic code connected to each excel file. This code, which can be seen in Appendix C, mainly used "if/then" statements to locate and count timestamps within the latitudes given by the reference lines created in ArcGIS. Therefore, by counting the timestamps, link travel times were able to be calculated for each of the four sections in both directions as well as for the entire corridor. This allows for a more in depth look at the effects on travel time of the improvements. The code outputs a travel time for each of the four sections as well as a total travel time for the entire run. Additionally, the code was pivotal in decreasing the amount of time required for travel time processing.

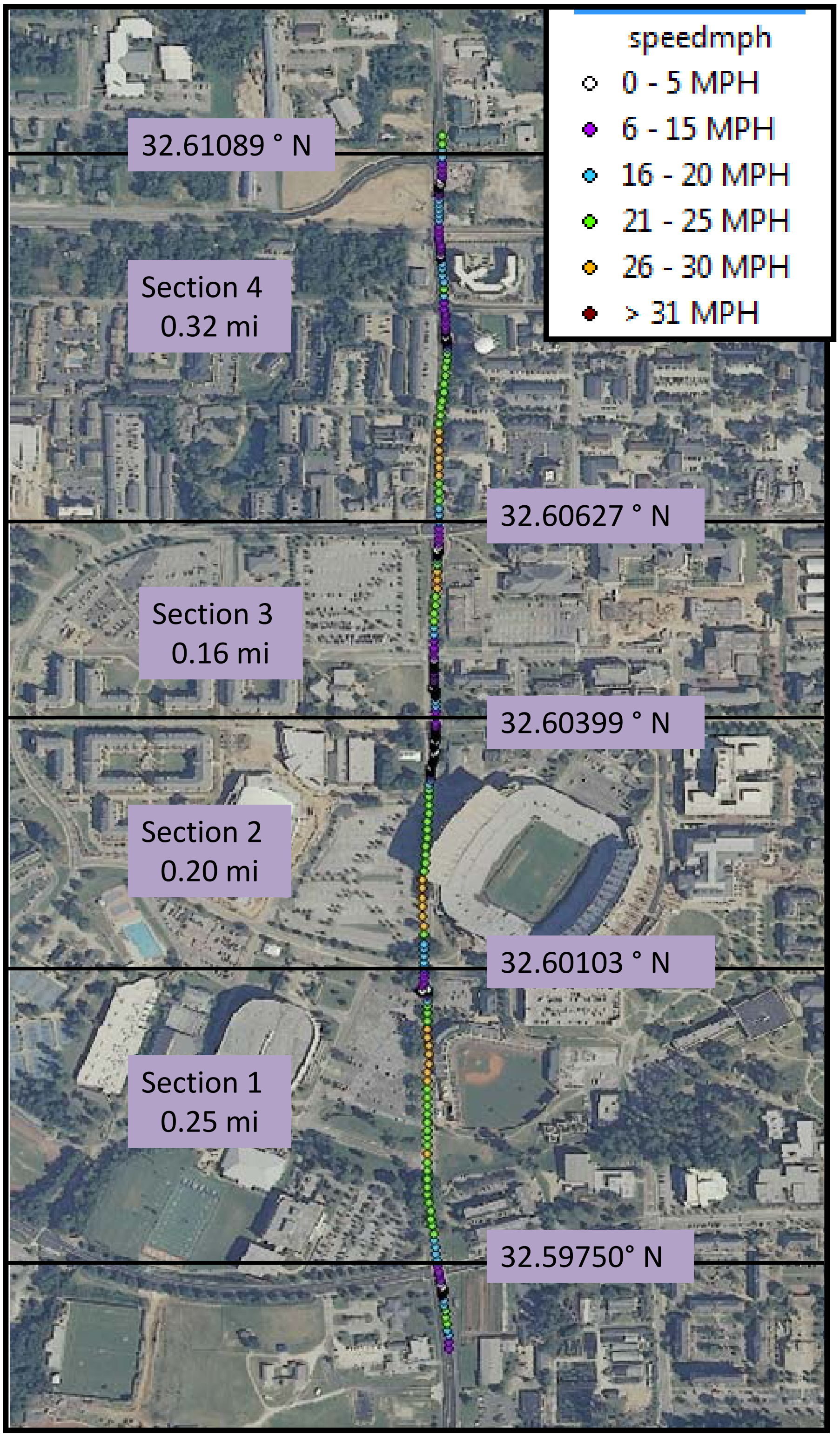


Figure 3.11 Travel Time Section Breakdown

In addition to computing travel times, the code also calculated the time spent in congestion (travelling under 10 mph) and the time spent stopped (travelling under 3 mph). The code simply counted up the number of timestamps that had a corresponding speed and were within the boundaries of the study corridor. These calculations are an interesting supplement to the overall travel time study, since increasing the time spent in congestion or stopped may be more frustrating to roadway users than increasing the overall travel time. While increasing the time spent in congestion directly corresponds to a higher overall travel time, a higher travel time may not mean more time spent in congestion.

3.3.3.2 Travel Time Analysis

The most important element of the study was the analysis of the changes made in travel times across the various improvement periods. Several different methods of analysis were evaluated before selecting the most effective. The paired t-test used in evaluating the changes in volume was reviewed; however, it was determined to limit the amount of parameters (i.e., link location, peak period, direction, and run number). To incorporate all of the parameters, it was determined that an analysis of variance (ANOVA) test should be performed. However, for regular ANOVA tests to be performed correctly, observations in any sample must be independent of observations in other samples. Because the parameters extended well beyond which collection period the data was collected in, the observations were not independent of each other. For example, a significant difference found between two collection periods could have been attributed to the various peak periods, directions, or days of the week rather than the actual improvements. Therefore, a nested ANOVA design was chosen as the best means of evaluating travel time differences across collection periods. This design called for a hierarchical structure of the parameters to be created prior to initiating the analysis. The top parameters on the hierarchical pyramid must have the greatest amount of difference between mean travel times when compared to the base categories. With each descending level, differences in mean travel time should decrease. Additionally, the test parameter (i.e., collection period) had to be placed at the bottom of the hierarchy. Several different hierarchies were designed before selecting the final hierarchy used in constructing a SAS code. The final hierarchy is shown in Figure 3.12. The model for the three-parameter nested design is shown in Equation 6.

$$y(ijkl) = \mu + \alpha_i + \beta_{j(i)} + \gamma_{k(ij)} + \epsilon_{(ijk)l} \begin{cases} i=1,2 \\ j=1,2,3 \\ k=1,2 \\ l=1,2,\ldots,n \end{cases} \tag{6}$$

Where:

$y(ijkl)$ = travel time across given sections of the study corridor

μ = constant term

α_i = the effect of the i^{th} direction on travel time

$\beta_{j(i)}$ = the effect of the j^{th} peak period only within the i^{th} direction

$\gamma_{k(ij)}$ = the effect of the k^{th} improvement period within the j^{th} peak period and i^{th} direction

€(ijk)l = the nested identically distributed (NID) $(0,\sigma^2)$ error term

As the analysis progresses down each nested level of the hierarchy, each parameter in question is treated as normally distributed. Therefore, each parameter's results are dependent upon the level they are nested (i.e., appear in the hierarchy).

The nested ANOVA test was run a total of 5 times for all of the travel time sections across the different levels in the hierarchy. The travel time sections tested were the total study corridor, Link Section 1, Link Section 2, Link Section 3, and Link Section 4. Therefore, traffic effects of individual improvements (i.e., new traffic signals, new pedestrian crosswalks, and signal coordination) were able to be further isolated from the overall corridor.

The null hypothesis (H_0) tests that the mean travel time value of the travel time section in question, regardless of the path down the hierarchy, are equal. Therefore, for each travel time section tested, every parameter level has no significant effect on the mean travel time value of that section. The alternative hypothesis (H_a) tests that the parameter path down the hierarchy will present a statistically significant difference in mean travel times for the section in question. The null and alternative hypotheses for each travel time section are summarized in Table 3.1.

Table 3.1 Nested ANOVA Null and Alternative Hypotheses Test for Travel Time Sections

Travel Time Section	Null Hypothesis (H_0)	Alternative Hypothesis (H_a)
1. Total Study Corridor	$\mu_1 = \ldots = \mu_{12}$	not all μ_i are equal
2. Link Section 1	$\mu_1 = \ldots = \mu_{12}$	not all μ_i are equal
3. Link Section 2	$\mu_1 = \ldots = \mu_{12}$	not all μ_i are equal
4. Link Section 3	$\mu_1 = \ldots = \mu_{12}$	not all μ_i are equal
5. Link Section 4	$\mu_1 = \ldots = \mu_{12}$	not all μ_i are equal

Again, SAS was used to run a code which reflected the hierarchy. The code output contained a p-value for each parameter level. At each level, the p-value indicates whether statistical significant differences exist between the parameters in that level. For example, the p-value for the peak period level indicates if there is a statistical significant difference between the AM, midday, and PM peak periods. A p-value under 0.05 again indicates statistical significant differences. As this process continued down the pyramid, datasets representing each of the parameters decreased in size. Therefore, at the bottom level of the hierarchy, each of the observations representing each heading contains only the same parameters above. For example, the before dataset for the northbound section of the AM peak period was only compared with the after dataset of the same direction and peak period, thus isolating the before and after (i.e., data collection period) scenarios for comparison.

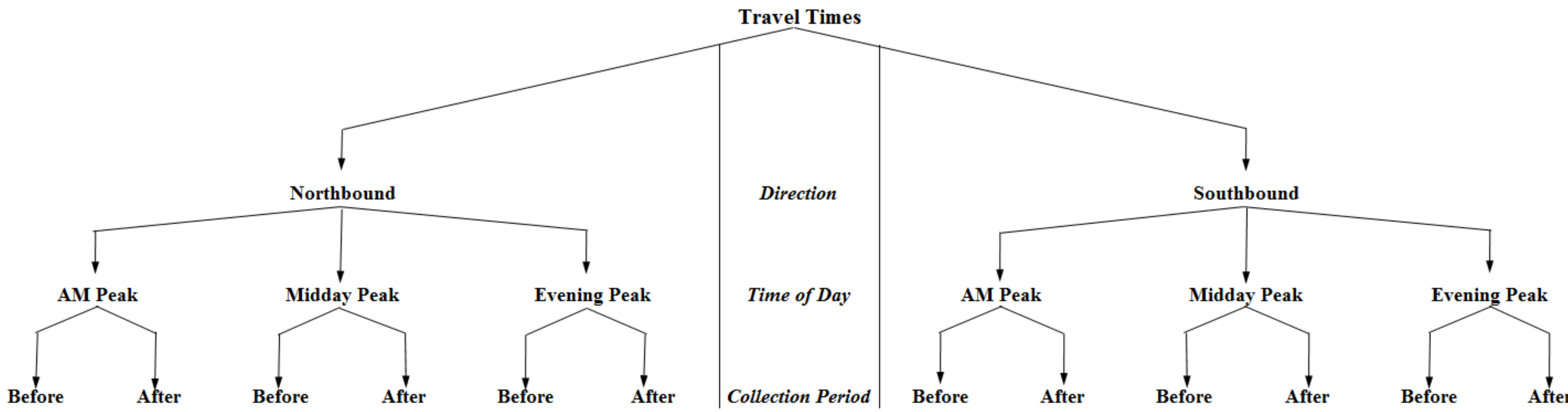


Figure 3.12 Hierarchical Structure for Parameters in Nested ANOVA Design

3.3.3.3 *Time Spent in Congestion and Time Spent Stopped Analyses*

Similarly to the study performed by Hutton et al., the amount of time spent in congestion and the amount of time spent stopped were evaluated from the travel time dataset (2010). As previously stated, the travel time Visual Basic® code also calculated the amount of that the vehicle spent in congestion (i.e., travelling < 10 mph) and the amount of time the vehicle spent stopped (i.e., travelling < 3 mph) time per each total travel time run. The congestion value of under 10 mph was arbitrarily selected based on the reviewed literature and the speed limit of 25 mph on the study corridor. As a supplement to the time spent in congestion and the time spent stopped, the percentage of time spent in congestion and the percentage of time spent stopped were calculated using the aforementioned measurements along with the total travel time. The amount and percentage of time spent in congestion as well as the amount and percentage of time spent stopped will be collectively referred to as the supplementary travel time parameters. Percent time spent in congestion and percent time spent stopped were calculated for each travel time run by Equation 6 and Equation 7, respectively:

$$Percent\ time\ in\ congestion = \left(\frac{Time\ Spent\ in\ Congestion}{Total\ Travel\ Time}\right) * 100 \quad (6)$$

$$Percent\ time\ stopped = \left(\frac{Time\ Spent\ Stopped}{Total\ Travel\ Time}\right) * 100 \quad (7)$$

This calculation was made for individual travel time runs. This calculation provided another parameter for analysis to determine whether the improvements had a statistically significant effect on the time spent in congestion and time spent stopped while factoring out changes in travel time.

Using the same style two-sided t-tests as in the speed analysis, a statistical analysis was conducted on both the amount and percent time spent in congestion and spent stopped. The null hypothesis and alternative hypothesis are stated as follows for each of the four supplementary travel time parameters in Equation 8 and Equation 9:

$$H_0 : \mu_{A(ij)} < \mu_{B(ij)} \tag{8}$$

$$H_a : \mu_{A(ij)} \geq \mu_{B(ij)} \tag{9}$$

Where:

H_0 = null hypothesis

H_a = alternative hypothesis

μ_A = mean supplementary travel time parameter during the after period

μ_B = mean supplementary travel time parameter during the before period

i = direction (north or south)

j = peak period (AM, MD, PM)

The test statistic, or t-value used in the t-test for time spent in congestion and time spent stopped analyses is as follows:

$$t = \frac{\mu_A - \mu_B}{S_p\sqrt{1/n_B + 1/n_A}} \tag{10}$$

Where:

t = test statistic for mean supplementary travel time parameters

μ_A= mean supplementary travel time parameter during the after period

μ_B = mean supplementary travel time parameter during the before period

s_p = pooled standard deviation

n_B = number of travel time observations collected during the before period

n_A = number of travel time observations collected during the after period

Again SAS® was used to conduct the t-tests at a significance level of 0.05. Each test outputted a test statistic and a p-value, which was used to determine statistically significant changes. For each of the four supplementary travel time datasets (i.e., amount of time spent in congestion, percent time spent in congestion, amount of time spent stopped, percent time spent stopped), 6 t-tests were conducted (i.e., three peak periods in either direction).

3.4 Summary of Methodology

The procedures for data collection, processing, and analysis were designed to isolate both the pedestrian and traffic effects of two separate sets of corridor improvements. Volumes, speeds, and travel times were collected for the two improvements datasets, Phase I: Intermediate Improvements and Phase II: Final Improvements, along with the pre-improvement scenario. After data collection, each set of raw data was processed into a dataset that was able to be analyzed according to the procedures for analysis developed from the reviewed literature. A series of different analysis types were used for each type of field collection: (1) a paired t-test was used to evaluate the differences in volumes across the improvement periods, (2) a simple two-sample t-test was designed to determine the significance of changes in mean speed across the improvement periods while also addressing 85th percentile speeds, and (3) a nested ANOVA test with a hierarchical design was used to evaluate mean travel time across the improvement periods for the entire corridor as well as for the four link travel time sections.

Table 3.2 effectively summarizes the design of the data collection, processing, and analysis methodology.

Table 3.2 Summary of Methodology for Data Collection and Analysis

Field Study	Purpose of Study	Method of Data Collection	Type of Analysis	Supplemental Information
Volume Study	To assess the changes in volume across each improvement period. The volume information also serves as a supplement to the two other studies by determining whether an increase/decrease in volume aided in significant changes in speed and travel time.	Vehicular volume was collected using traffic counters and pneumatic tubes. Collection occurred at four midblock locations on the study corridor. These locations were selected to correlate with the four link sections used in travel time study.	Volumes were aggregated into 8 15-minute blocks per each peak period. Each block was averaged across all 5 days and paired with the corresponding block in another improvement period. A paired t-test was run in SAS to determine whether significant changes occurred across improvement periods.	
Speed Study	To asses changes in speed at midblock locations to determine the improvements effects on traffic throughput as well traffic calming for pedestrian safety	Speeds were collected using the same four traffic counters and pneumatic tube setups as the volume study. The choice of collecting at midblock locations was made so that free flow speeds would be collected.	Simple two sample t-tests were used to compare the mean speeds at each of the four locations during each peak period.	
Travel Time Study	To evaluate the changes in travel time across each improvement period in order to assess the overall effect of the improvements. Additionally, to further evaluate the improvements, the corridor was divided into four link sections.	Travel times were collected using the GPS test vehicle technique previously discussed in Section 2.2.2. During every peak period, 6 full corridor runs in each direction were made over 6 collection days. Position (latitude) and speed were collected at one second intervals as the vehicle traveled down the corridor.	Before analysis was performed, the raw position and speed data was processed into total travel time and four link travel times using a Visual Basic Code. A nested ANOVA test with a hierarchical design was then used to evaluate any significant changes in total and link travel times. The hierarchical design allows for the improvement periods to be isolated away from other parameters such as peak period or direction.	The Visual Basic Code that calculated travel times also was used to calculate the amount of time spent in congestion (<10 mph) and the amount of time spent stopped (< 3 mph) during the travel time collection. While this data was not formally analyzed, it was used as an important supplement to the travel time results.

Chapter 4: Experimental Analysis Results and Discussion

4.1 Introduction

This chapter will present the results generated from experiments and the statistical analyses used to evaluate the performance of traffic and pedestrian improvements made on Donahue Drive. The chapter will focus on the effects of the Intermediate Improvements as compared with the Pre-improvement scenario. Comparisons between the Final Improvements and the Pre-improvement scenario are not reported due to delay associated with the installation of the traffic signal coordination equipment. The results are divided into subsections based on the three sets of collected parameters (i.e., volume, speed, and travel time). Each subsection will summarize the results from each field study after data processing has occurred and the statistical analyses performed. As previously stated, the main objective of each study was to evaluate the improvements based on the three different study parameters (i.e., volume, speed, and travel time).

4.2 Pre-Improvement and Intermediate Improvement Analyses and Results

This section will present the results of analyses performed to compare the Pre-improvement scenario (baseline) and the Intermediate Improvement Phase. For each parameter study, the results of the statistical analyses are summarized and presented accordingly.

4.2.1 Volume Study

Vehicular volumes were collected and analyzed according to the procedures discussed in *Chapter 3*. Analyses were performed using a series of paired t-tests which evaluates the statistical significance of the difference between the pre-improvement and intermediate improvement dataset at the same time and counter location. The results of the comparison between the pre-improvement period volumes and the intermediate-improvement volumes using paired t-tests for the northbound and southbound traffic volumes across all 4 counter locations are also shown in Table 4.1 and Table 4.2, respectively. The tables show the average weekly volumes (i.e., Monday – Friday) of the 8, 15-minute blocks for each counter location during each peak period across the improvement periods (i.e., μ_B and μ_A correspond to the mean volumes for the pre-improvement and intermediate improvement periods, respectively.). Additionally, the table indicates whether a statistically significant change (i.e., a p-value > 0.05) occurred. The statistical analyses were performed on the entire dataset, which included the averages of all 5 days during the data collection periods.

Table 4.1 Northbound Volume Results and Analysis

Peak Period	Time Period	Counter 1						Counter 2						Counter 3						Counter 4					
		μ_B	μ_A	μ_B-μ_A	t-value	p-value	Sig?	μ_B	μ_A	μ_B-μ_A	t-value	p-value	Sig?	μ_B	μ_A	μ_B-μ_A	t-value	p-value	Sig?	μ_B	μ_A	μ_B-μ_A	t-value	p-value	Sig?
	7:30	94	96	-2				63	59	4				22	24	-2				33	42	-9			
	7:45	97	91	7				63	43	20				25	25	-1				30	43	-13			
	8:00	60	69	-9				36	44	-8				26	30	-4				36	40	-4			
	8:15	56	60	-4				30	30	0				31	27	4				33	32	2			
AM Peak	8:30	54	62	-8	-1.83	0.0739	No	29	27	2	0.32	0.7470	No	30	30	-1	-0.21	0.8321	No	32	37	-5	0.40	0.6800	No
	8:45	57	70	-13				35	36	-1				37	43	-6				38	53	-15			
	9:00	55	60	-5				42	40	1				50	43	7				58	51	8			
	9:15	52	56	-4				42	34	9				41	41	0				48	52	-4			
	9:30	51	53	-2				34	35	-1				42	39	3				44	44	0			
	11:30	57	58	-1				46	47	-1				67	63	3				74	79	-5			
	11:45	65	68	-3				59	54	5				87	79	8				79	93	-14			
	12:00	73	77	-4				64	64	0				81	80	1				95	101	-7			
	12:15	69	75	-6				64	53	11				71	60	11				80	89	-9			
Midday Peak	12:30	67	78	-11	-1.41	0.1656	No	60	61	-1	3.21	**0.0025**	**Yes**	71	63	8	-0.62	0.5415	No	78	85	-7	-3.71	**0.0006**	**Yes**
	12:45	73	76	-3				58	55	3				64	59	5				78	79	-1			
	13:00	59	63	-4				55	59	-4				66	71	-5				93	91	2			
	13:15	60	69	-9				56	58	-2				66	60	5				75	75	-1			
	13:30	74	73	1				54	59	-5				56	65	-10				73	89	-15			
	4:30	69	85	-16				72	71	1				99	91	8				98	111	-13			
	4:45	82	96	-14				75	74	1				101	90	11				98	119	-21			
	5:00	74	106	-32				42	83	-41				95	106	-11				96	126	-30			
	5:15	74	115	-41				60	85	-25				90	88	2				97	115	-19			
PM Peak	5:30	78	107	-28	0.07	**<.0001**	**Yes**	68	84	-16	0.07	0.9415	No	82	81	1	-2.84	**0.0068**	**Yes**	94	109	-15	-7.24	**<.0001**	**Yes**
	5:45	79	111	-33				70	88	-18				78	77	1				86	97	-11			
	6:00	75	99	-24				60	86	-27				96	90	7				92	116	-24			
	6:15	75	87	-12				62	77	-14				85	81	4				89	108	-19			
	6:30	71	83	-12				78	76	2				81	67	14				86	99	-13			

Note: μ_B = number of vehicles crossing a counter during the before scenario
μ_A = number of vehicles crossing a counter during the after scenario

Table 4.2 Southbound Volume Results and Analysis

Peak Period	Time Period	Counter 1						Counter 2						Counter 3						Counter 4					
		μ_B	μ_A	μ_B-μ_A	t-value	p-value	Sig?	μ_B	μ_A	μ_B-μ_A	t-value	p-value	Sig?	μ_B	μ_A	μ_B-μ_A	t-value	p-value	Sig?	μ_B	μ_A	μ_B-μ_A	t-value	p-value	Sig?
AM Peak	7:30	34	41	-7				72	80	-8				123	125	-2				161	176	-15			
	7:45	43	50	-7				86	94	-8				147	118	29				194	164	30			
	8:00	47	53	-5				85	83	2				101	95	6				95	98	-3			
	8:15	41	47	-6				82	76	6				86	79	7				82	91	-9			
	8:30	41	45	-4	-2.05	**0.0461**	**Yes**	86	82	3	1.67	0.1018	No	87	88	-1	-1.74	0.8321	No	97	107	-10	-1.79	0.0796	No
	8:45	54	53	0				95	83	12				87	82	5				106	102	4			
	9:00	58	60	-2				88	88	0				70	69	1				84	93	-9			
	9:15	54	52	2				79	79	0				68	64	4				89	91	-2			
	9:30	54	49	5				84	77	8				74	61	13				79	77	2			
Midday Peak	11:30	70	72	-1				88	85	4				67	61	6				75	88	-14			
	11:45	70	77	-7				79	80	-1				71	67	4				82	89	-7			
	12:00	87	86	1				96	79	17				70	69	2				81	96	-15			
	12:15	73	74	-1				82	75	7				77	70	7				84	97	-13			
	12:30	72	77	-5	-3.01	**0.0043**	**Yes**	91	83	7	0.39	0.6958	No	80	79	1	-1.98	0.0545	No	81	101	-19	-1.54	0.1303	No
	12:45	78	72	6				93	86	8				95	79	16				101	103	-2			
	13:00	81	83	-2				89	86	3				74	59	15				74	82	-8			
	13:15	66	71	-5				82	79	3				70	67	3				78	84	-6			
	13:30	73	79	-6				88	89	-1				76	77	-2				100	110	-11			
PM Peak	4:30	86	98	-12				93	95	-2				66	70	-4				73	95	-22			
	4:45	99	105	-7				112	100	11				78	87	-8				76	103	-27			
	5:00	90	103	-13				96	92	5				67	66	1				67	80	-13			
	5:15	84	93	-9				93	92	1				73	81	-9				70	96	-26			
	5:30	74	89	-15	-6.66	**<.0001**	**Yes**	92	90	2	-4.57	**<.0001**	**Yes**	79	82	-2	-1.68	0.0995	No	91	116	-25	-8.07	**<.0001**	**Yes**
	5:45	86	93	-7				94	91	4				86	88	-2				91	115	-24			
	6:00	95	94	1				85	79	7				71	73	-1				75	90	-15			
	6:15	84	93	-9				70	81	-11				75	76	-1				81	94	-12			
	6:30	71	98	-27				70	78	-8				74	68	6				77	94	-16			

Note: μ_B = number of vehicles crossing a counter during the before scenario
μ_A = number of vehicles crossing a counter during the after scenario

Table 4.1 summarizes the traffic volume travelling northbound along the study corridor, Donahue Drive. In the northbound direction, the largest volumes for the AM peak occur at counters 1 and 2, with much smaller volumes recorded at counters 3 and 4. For the Midday and PM peak periods, Counters 3 and 4 experience larger volumes than counters 1 and 2, as vehicles are exiting campus to the north. These results indicate that in both directions, the majority of vehicles travel towards the central part of campus (i.e., the campus core) during the AM peak period, and travel away from campus in both directions during the Midday and PM peak periods. Overall, the PM peak period receives the greatest volumes in both the northbound and southbound directions.

The southbound results, shown in Table 4.2, indicate that the largest volumes occur at Counter 4, which is located approximately midway between two major arterials, W. Glenn Ave. and W. Magnolia Ave. Therefore, this counter location experiences a high volume of vehicles travelling to the CBD in addition to vehicles attempting to access the campus core, thus causing it to experience higher volumes than the other counter locations. If a vehicle was traveling southbound, it would traverse higher counter numbers to lower numbers (e.g., 4 to 1). Therefore, in the AM peak, the majority of traffic is traveling southbound from the northernmost location, counter 4. A considerable amount of vehicles seem to turn as vehicles travel southbound past counters 3 and 2. These locations correspond with the student parking lots on campus. For the midday and PM peak periods, greater volumes occur in the southbound direction at counters 1 and 2, as students and university employees are exiting campus to the south.

In the volume analyses, t-values and p-values were calculated in SAS® and used to determine whether statistically significant changes occurred in volume across the two improvement periods. At a 95% confidence interval (i.e., $\alpha = 0.05$), a statistically significant change was determined if the p-value was less than 0.05. These p-values are shown in bold in the table. In the southbound direction, a statistically significant change was determined in five of the twelve paired t-tests. All changes to the volumes at counter 1 were determined to be significantly different. These differences may be attributed to the fact that counter 1 received the fewest amount of traffic of all of the counters. No significant changes occurred at counter 3. An increase in volume was observed in all but four of the twelve tests (i.e., the AM and Midday Peaks for counters 2 and 3, none of which were significant).

In the northbound direction, again 5 of the 12 t-tests determined statistically significant changes in volume. At least one significant difference occurred at each counter location. Three reductions in average volume occurred from the pre-improvement period to the intermediate improvement period: the AM and Midday Peak Periods for counter 2 and the PM peak period for counter 3. Contrary to the southbound volume reductions, both the reductions for counter 2 Midday peak volumes and the counter 3 PM peak volume were statistically significant.

In both directions, the PM peak periods experienced statistically significant changes for six out of the eight possible tests. It is important to note that across all counter locations, the PM peak period experienced the highest volumes. This fact is important because the PM peak period likely does not represent students arriving or departing campus as much as it does university employees departing campus on their evening commutes.

The volume results are important to the travel time and speed analysis as well. Statistically significant changes in travel times and speeds can be caused by an increase or decrease in the volume demands of the roadway, thus nullifying the effects of the intermediate improvements. To truly isolate the effects of the improvements, statistically significant changes in volume would not have occurred across improvement periods. However, since just under half of the peak period volumes experienced statistically significant results across improvement periods, discarding those results would be short sided, greatly reducing the thoroughness of the overall scope of the project. The statistical differences in volume can possibly be explained by factors such as a greater enrollment across the improvement periods (i.e., the intermediate improvement was collected a full year after the pre-improvement period), increased traffic demand caused by various campus events (e.g., sorority chapter meetings, campus social events), and by the inexact nature of traffic demand on campus. Therefore, the peak periods with significant changes in volume were included and noted in travel time and speed analysis.

4.2.2 Speed Study

The speed study was performed to evaluate the overall changes in speed at the four counter locations presumed to be caused by the intermediate improvements previously listed in Section 1.2. The intermediate improvements were a response to increasing pedestrian safety for pedestrians crossing Donahue as well as an attempt to increase the efficiency of the Tiger Transit Bus System by allocating a street for transit arrivals and departures.

The speed results for the pre-improvement scenario largely correlate to the vehicular volume results discussed in Section 4.2.1. According to basic traffic flow theory, as volume increases on a roadway approaching the jam density, speeds should decrease and conversely, as volume decreases below the critical density, speeds should increase (Roess, Prassas et al. 2004).

The overall results from the paired t-test analyses are shown in Table 4.3 for the northbound direction and Table 4.4 for the southbound direction. In addition to displaying the mean speed, standard deviation, and number of observations for each peak period, the tables also include the results of the analysis. The determination of statistically significant changes were made in the same way as in the volume study, based upon the p-values in the table. Additionally, the tables show any statistically significant increase in volume, which can begin to explain irregularities in speed changes. A significant increase in volume can lead to a reduction in mean speeds as volume approaches the jam density as previously mentioned.

Table 4.3 Results of Northbound Speed Analyses

Counter Number	Peak Period	Increase in Volume?	Before n	Before μ_B (mph)	Before σ(mph)	After n	After μ_A(mph)	After σ(mph)	t-value	Variances Equal?	p-value	Significant Difference
Counter 1	AM	No	2,601	21.98	4.59	2,665	22.76	4.47	6.28	yes	**<.0001**	**yes**
	Midday	No	2,590	21.33	4.67	2,626	22.26	4.82	7.15	yes	**<.0001**	**yes**
	PM	Yes	2,990	24.08	4.56	3,529	23.39	4.64	4.72	yes	**<.0001**	**yes**
Counter 2	AM	No	1,669	23.12	4.82	1,388	21.09	5.21	-11.07	no	**<.0001**	**yes**
	Midday	Yes	2,291	23.99	4.62	2,509	21.27	5.38	-18.81	no	**<.0001**	**yes**
	PM	No	2,508	22.97	7.34	3,529	24.07	4.64	6.69	no	**<.0001**	**yes**
Counter 3	AM	No	1,304	25.22	4.32	1,360	24.14	4.25	-6.49	yes	**<.0001**	**yes**
	Midday	No	2,854	24.85	4.25	2,886	23.49	4.29	-12.01	yes	**<.0001**	**yes**
	PM	Yes	3,637	24.52	4.81	3,810	22.81	4.84	-15.21	yes	**<.0001**	**yes**
Counter 4	AM	No	1,523	25.27	4.96	1,666	25.22	4.43	-0.29	no	0.772	no
	Midday	Yes	3,202	22.48	6.08	2,954	22.18	6.02	1.02	yes	0.0564	no
	PM	Yes	3,669	20.19	6.18	3,310	20.21	6.22	1.06	yes	0.8553	no

Note: n = number of observations;
μ = mean speed (mph);
σ = standard deviation of speed (mph);
Before = Pre-improvement conditions (Collected 3/29/10 – 4/2/10);r
After = Intermediate Improvement Conditions (Collected 4/4/11 – 4/8/11)

Table 4.4 Results of Southbound Speed Analyses

Counter Number	Peak Period	Increase in Volume?	Before n	Before μ_B(mph)	Before σ(mph)	After n	After μ_A(mph)	After σ(mph)	t-value	Variances Equal?	p-value	Significant Difference
Counter 1	AM	Yes	1,832	22.97	5.73	1,872	21.53	5.38	-7.92	no	**<.0001**	**yes**
	Midday	Yes	2,938	23.30	21.58	2,827	21.59	5.40	-12.06	yes	**<.0001**	**yes**
	PM	Yes	3,439	25.01	5.74	3,586	23.34	5.30	-12.24	no	**<.0001**	**yes**
Counter 2	AM	No	2,957	21.88	4.68	3,246	21.87	5.11	-0.06	no	0.9537	no
	Midday	No	3,431	22.97	4.70	2,852	21.17	5.46	-14.18	no	**<.0001**	**yes**
	PM	Yes	3,634	24.74	5.00	3,587	23.40	5.30	-11.09	no	**<.0001**	**yes**
Counter 3	AM	No	3,443	21.39	6.02	3,632	22.32	5.97	6.5	yes	**<.0001**	**yes**
	Midday	No	2,956	22.37	5.71	2,842	22.25	5.83	-0.75	yes	0.4531	no
	PM	No	2,918	23.28	5.50	3,044	23.89	5.28	4.39	no	**<.0001**	**yes**
Counter 4	AM	No	4,508	27.91	4.42	4,135	28.18	4.96	2.61	no	**0.0091**	**yes**
	Midday	No	3,249	28.27	4.11	3,163	28.42	4.42	1.39	no	0.1642	no
	PM	Yes	3,094	28.37	4.31	2,976	28.79	4.21	3.81	yes	**<.0001**	**yes**

Note: n = number of observations;
μ = mean speed (mph);
σ = standard deviation of speed (mph);
Before = Pre-improvement conditions (Collected 3/29/10 – 4/2/10);
After = Intermediate Improvement Conditions (Collected 4/4/11 – 4/8/11)

In the northbound direction, statistically significant changes in speed occurred at counter 1, 2, and 3 for all three peak periods. Only the changes in speeds at counter 4 were not statistically significant across the two collection periods. At counter 1, speed increased during the AM and Midday peak periods, yet decreased during the PM peak period. However, counter 1 experienced a statistically significant increase in volume during the PM peak period, which largely explains the statistically significant reduction in speeds during this time period. At Counter 2, significantly reduced speeds occurred during the AM and Midday peak periods, yet speed significantly increased during the PM peak period. Because of the pedestrian nature of the intermediate improvements (i.e., installation of a speed table w/integrated raised pedestrian crosswalk at Thach Concourse, addition of pedestrian features to the traffic signal at South Heisman Drive Intersection), reductions in speed would be expected at counter 2 due to its proximity to the areas where the improvements were implemented. The statistically significant rise in speed during the PM peak period perhaps occurred because of less pedestrians crossing the corridor since most students finish classes well before the PM peak period. Counter 3 recorded the highest mean speeds in the northbound direction. Each peak periods experienced a statistically significant reduction in mean speed. The significant rise was expected because of counter 3's location, downstream from the intermediate improvement area around section 2 in the northbound direction. Traffic counter 4 was the only location that did not experience any statistically significant change in speed across the intermediate improvement period. This is to be expected since it is not located adjacent to campus like the other three counters. Additionally, the location around counter 4 does not experience high pedestrian volumes that lead to more variability in speed than the other on-campus counter locations. This leads counter 4 to experience free flow speeds since users are accelerating after departing from the high pedestrian zones adjacent to campus. Counter 4 largely performed as expected based on simple traffic flow theory, recording its highest speeds in the AM peak.

In the southbound direction, shown in Table 4.4, 9 of the 12 peak periods recorded statistically significant changes in speed. Counter 1, which is downstream of the intermediate improvement areas in the southbound direction, experienced statistically significant reductions in mean speed as expected. The southbound results for counter 1 behave similarly to the northbound results for counter 3, since both are immediately downstream of the intermediate improvements around counter 2 designed to improve pedestrian safety. Counter 2 experienced statistically significant reductions in speed during the Midday and PM peak periods, while experiencing no change in speed during the AM peak period. As previously stated, a reduction in mean speed was expected at counter 2 because of its proximity to the intermediate improvements. Counter 3 actually experienced a statistically significant rise in speed during the AM and Midday peak periods. Since the intermediate improvements were located further downstream from counter 3, they did not directly influence the southbound results for counter 3. Again, the southbound results for counter 3 showed many similarities to the northbound results for counter 1. The largest speeds and highest volumes recorded at any location in either direction occurred in the southbound direction at counter 4. Statistically significant rises in speed occurred during the AM and PM peak periods at counter 4. As previously stated, the very different results of counter 4 when compared to the other counter results can be attributed to its off-campus location. Even with the significant increases in speeds, counter 4 experienced the smallest amount of variability in both directions. It should be noted that even though 9 of the 12 peak periods tested experienced statistically significant changes, only 2 peak periods experienced a change in mean speed over 2.0 mph. The northbound AM and Midday peak periods at counter 2 experienced reductions of 2.03 mph and 2.72 mph, respectively. Since these results bear little practical significance, safety conclusions drawn from the speed study must not be immediately drawn in evaluating the performance of the intermediate improvements.

In summary, the intermediate improvements' overall impacts on speed for traffic analysis were predictable based on the objectives of the improvements. For the most part, the improvements caused significant reductions in speed in the locations that they immediately affected. Counters 1, 2, and 3 exhibited largely different speed behavior from counter 4 as a result of higher pedestrian crossings. Additionally, traffic flow theory largely held true when analyzing the effects of volume on speed.

4.2.3 Travel Time Study

The travel times study section is divided into two smaller sections: (1) travel time analyses and results and (2) amount of time spent in congestion or stopped. Both of these sections were collected using the GPS test vehicle method as discussed in *Section 3.2.3.* While the results may be similar since they are both processed from the same raw datasets, they provide different insight into how the intermediate improvements affect the roadway.

4.2.3.1 Travel Time Analyses and Results

The most important analyses performed in the study are the travel time results. Travel times were collected using a GPS device attached to a vehicle as it traversed the corridor and calculated using a Visual Basic code. As previously discussed in *Section 3.3.3.2*, a nested ANOVA design was used to carry out the statistical analysis for travel times across the entire corridor as well as link travel times between major intersections. The nested ANOVA test carries a hierarchical design that evaluates the study parameters from most independent to least. The design first evaluates directional (i.e, northbound / southbound) effects on travel times, followed by peak period effects (i.e., AM, Midday, or PM), with collection period effects being evaluated last. This hierarchy, shown in Figure 4.1 ensures that on the final level, only travel times of the same direction and peak period will be evaluated for statistical significance based on the improvement period under consideration.

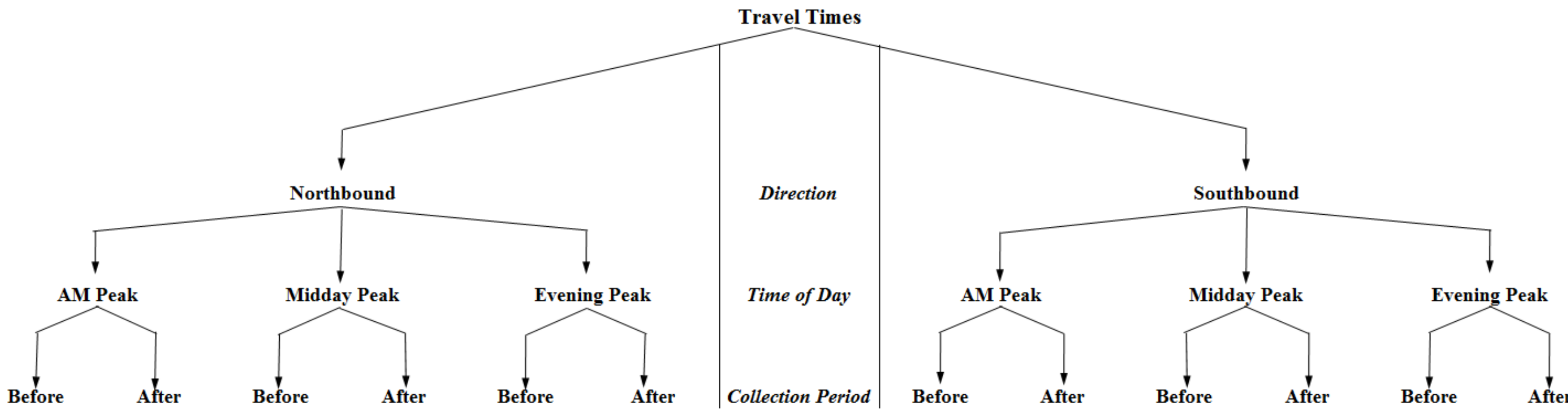


Figure 4.1 Travel Time Hierarchy Tree Design

The results after performing the nested ANOVA test for the entire corridor are shown in Table 4.5. The table shows the direct output from SAS® and gives p-values for the entire travel time data set as well as for each of the parameters in the hierarchy. For the 335 travel times collected in the analysis, the average time collected was 267.83 seconds. Additionally, the R-squared test that evaluates the statistical model was very low, at 0.230411.

Table 4.5 Nested ANOVA Test Results for the Entire Corridor

Source	DF	Squares	Mean Square	F-Value	Pr > F
Model	8	500946.507	62618.313	12.2	<.0001
Error	326	1673196.794	5132.506		
Corrected Total	334	2174143.301			
	R^2	**Coeff Var**	**Root MSE**	**Mean**	
	0.230411	26.74889	71.64151	267.8299	

Source	DF	Type I SS	Mean Square	F-Value	Pr> F
Direction	1	45329.6066	45329.6066	8.83	0.0032
Peak Period(Direction)	4	320576.5033	80144.1258	15.62	<.0001
Improvement Period(Peak Period)	3	135040.3974	45013.4658	8.77	<.0001

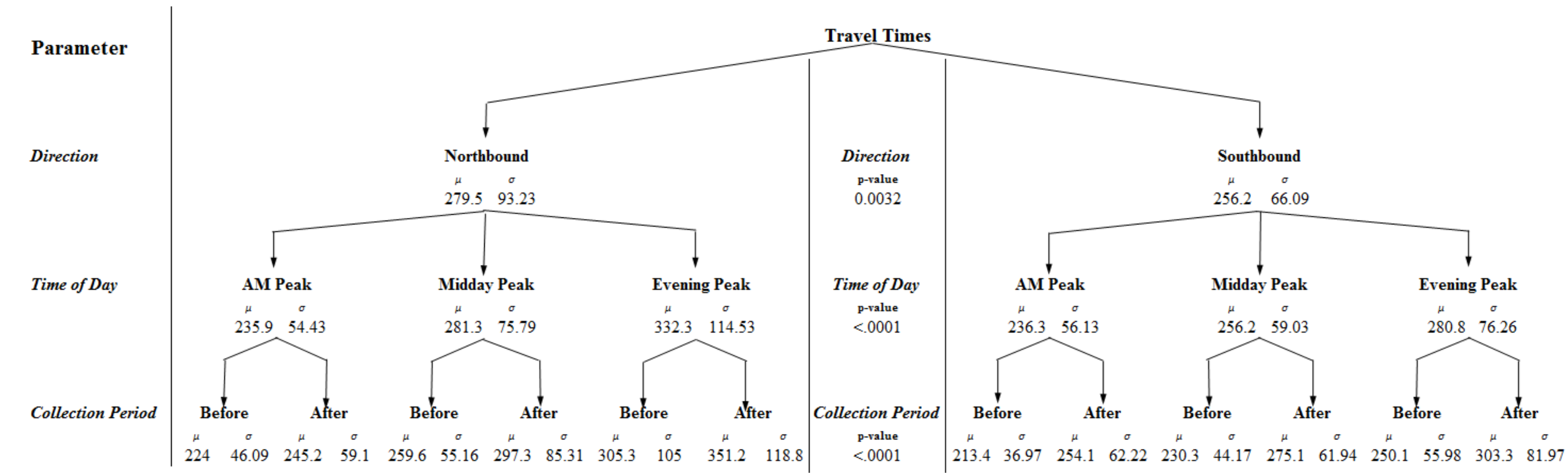
At the bottom of the table, all three parameters (i.e., direction, peak period, and improvement period exhibit a statistically significant impact on travel time. While it may seem obvious that direction and peak period would display statistical significance, it is the statistically significant difference of the improvement period that confirms that the hypothesis stating that travel times will significantly increase across the intermediate improvement period. Since the Improvement Period parameter resulted in a p-value of less than 0.0001, statistically significant changes in travel time occurred based on the intermediate improvements made on the roadway.

To further enhance the analysis results presented in Table 4.5, a hierarchical design tree with mean and standard deviation values was created and is shown in Figure

4.2. Since direction should have the largest effect on travel time, it was decided to be the first parameter in the hierarchy. The northbound direction resulted in a mean travel time of 279.5 seconds, which is 23.4 seconds higher than the mean travel time for the southbound direction, 256.2 seconds. Peak period was the next parameter tested in the hierarchy, with the evening peak period in both directions experiencing the largest travel times. This corresponds with the fact that the evening peak period experienced the largest volumes, as previously stated in Section 4.2.1. Moreover, the northbound PM peak period experienced a mean travel time of 332.3 seconds, which is 51 seconds longer than the next longest average peak period in the northbound direction, occurring during the Midday Peak. The AM peak in both directions experienced the shortest travel times on average. Very little difference exists between the northbound and southbound AM peak periods, which experienced mean travel times of 235.9 seconds and 236.3 seconds, respectively.

Collection period was selected as the final level of the hierarchy so that travel times of the same direction and peak period would be grouped together, thus isolating collection period as the only possible explanation for statistically significant differences. For every peak period in both directions, travel times experienced a statistically significant increase from the pre-improvement period to the intermediate improvement period. Therefore, the improvements made during the intermediate improvement phase actually increased travel times in both directions during all peak periods. Mean travel times increased by an average of 40 seconds across all peak periods in both directions, with the largest average increase, 53.2 seconds, occurring in the southbound PM peak period. While it may have been expected that a reduction in travel times would occur after the intermediate improvements were installed, it should be noted that the aim of these improvements was aimed towards improving pedestrian safety and increasing the efficiency of the Tiger Transit system.

The PM peak period also experienced the largest standard deviations across all directions. The large variability in travel times during the PM peak period may be explained by large fluctuations in vehicular volume based on various evening campus events (e.g., sorority chapter meetings). Additionally, during the PM peak period at the Thach Pedestrian Concourse Intersection, the on-duty traffic crossing guard's shift ends, thus changing the intersection controller to a stop sign. This event greatly changes the makeup of the corridor, leading to increased traffic queuing which causes travel times to increase and become more inconsistent.



Note: μ = mean travel time (seconds);
σ = standard deviation of travel time (seconds)

Figure 4.2 Travel Time Hierarchical Design Tree for Nested ANOVA Test on Entire Corridor

To more accurately explain the statistically significant increases in travel time down the corridor under consideration, the mean travel times from each of the four link sections described in *Section 3.3.3* were analyzed using the same nested ANOVA test as used on the entire corridor. Of the four link sections, two sections, Section 2 and Section 4, experienced statistically significant changes to mean travel time. Table 4.6 shows the SAS® output of each of the four link sections.

Table 4.6 Nested ANOVA Test Results for Link Sections 1-4

Section 1

Source	DF	Squares	Mean Square	F-Value	Pr > F
Model	8	12846.2895	1605.7862	2.45	0.0139
Error	326	213984.6538	656.3946		
Corrected Total	334	226830.9433			

R^2	Coeff Var	Root MSE	Mean
0.056634	45.02317	25.6202	56.90448

Source	DF	Type I SS	Mean Square	F-Value	Pr> F
Direction	1	526.811404	526.811404	0.8	0.371
Peak Period(Direction)	4	8605.137135	2151.284284	3.28	0.0118
Improvement Period(Peak Period)	3	3714.340913	1238.113638	1.89	0.1317

Section 2

Source	DF	Squares	Mean Square	F-Value	Pr > F
Model	8	62751.5359	7843.942	8.88	<.0001
Error	326	287880.1477	883.0679		
Corrected Total	334	350631.6836			

R^2	Coeff Var	Root MSE	Mean
0.178967	53.00577	29.71646	56.06269

Source	DF	Type I SS	Mean Square	F-Value	Pr> F
Direction	1	6096.23391	6096.23391	6.9	0.009
Peak Period(Direction)	4	30488.14858	7622.03714	8.63	<.0001
Improvement Period(Peak Period)	3	26167.15344	8722.38448	9.88	<.0001

Section 3

Source	DF	Squares	Mean Square	F-Value	Pr > F
Model	8	50879.0835	6359.8854	7.25	<.0001
Error	326	285833.1374	876.7888		
Corrected Total	334	336712.2209			

R^2	Coeff Var	Root MSE	Mean
0.151106	51.34612	29.61062	57.66866

Source	DF	Type I SS	Mean Square	F-Value	Pr> F
Direction	1	11592.74495	11592.74495	13.22	0.0003
Peak Period(Direction)	4	35008.67624	8752.16906	9.98	<.0001
Improvement Period(Peak Period)	3	4277.66229	1425.88743	1.63	0.1831

Section 4

Source	DF	Squares	Mean Square	F-Value	Pr > F
Model	8	40130.086	5016.2607	4.13	0.0001
Error	326	395592.3021	1213.4733		
Corrected Total	334	435722.3881			

R^2	Coeff Var	Root MSE	Mean
0.0921	35.84062	34.83494	97.19403

Source	DF	Type I SS	Mean Square	F-Value	Pr> F
Direction	1	2511.20115	2511.20115	2.07	0.1512
Peak Period(Direction)	4	23557.94591	5889.48648	4.85	0.0008
Improvement Period(Peak Period)	3	14060.93892	4686.97964	3.86	0.0097

Table 4.6 shows that each of the link sections went through the same nested ANOVA testing as the entire corridor. This allows for the individual effects of the improvements to be more easily detected. Figure 4.3 was created to give a better visual perspective of the link section travel time analysis overlaid onto an aerial photo illustrating the link sections. The intersections marked A, B, and C indicate where the intermediate improvements took place. The most statistically significant change in travel time occurred at Link Section 2, which experienced a 17.74 second increase in mean travel time and a p-value ≤ 0.0001. The intermediate improvements, whose primary objective was to increase pedestrian safety, clearly affect Link Section 2 more than any other section. Therefore, it is without surprise that the most significant increase in travel time occurred at Link Section 2.

Section 4

Period	μ	σ	p-value	Significance
Before	91.42	35.08	**0.0097**	**Yes**
After	101.49	36.37		

Section 3

Period	μ	σ	p-value	Significance
Before	53.70	29.00	0.1831	No
After	60.63	33.42		

Section 2

Period	μ	σ	p-value	Significance
Before	45.90	22.34	**<.0001**	**Yes**
After	63.64	36.47		

Section 1

Period	μ	σ	p-value	Significance
Before	53.3	22.3	0.1317	No
After	59.6	28.3		

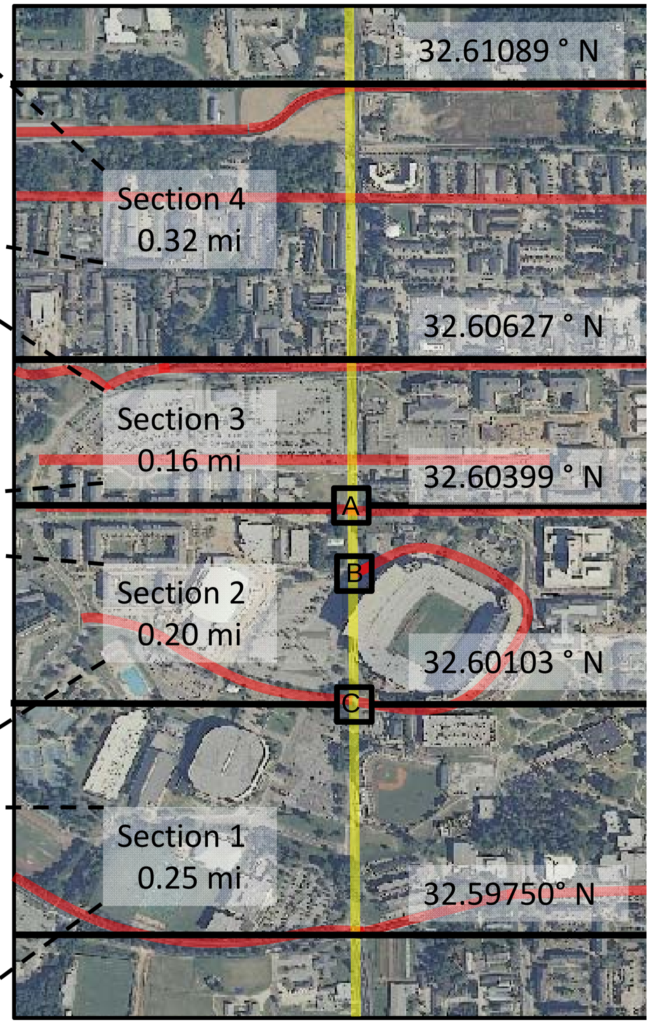


Figure 4.3 Link Travel Time Sections with Analysis Tables

Note: Intersections A, B, and C indicate areas where intermediate improvements took place
μ = mean travel time (sec);
σ = standard deviation of travel time (sec);
Before = Pre-improvement conditions (Collected 3/29/10 – 4/2/10);
After= Intermediate Improvement Conditions (Collected 4/4/11 – 4/8/11)

The other statistically significant increase in travel time occurred at Section 4, which experienced higher volumes in both the pre-improvement and intermediate improvement periods. According to the volume study discussed in Section 4.2.1, Table 4.1, and Table 4.2, an increase in mean volume occurred for all six peak periods tested (i.e., 3 northbound / 3 southbound) at traffic Counter 4. Of the six peak periods, three of the increases were statistically significant: the northbound midday peak, northbound PM peak, and the southbound PM peak. Additionally, since Link Section 4 is geographically the longest section at 0.32 mi, its travel time theoretically should vary more than any of the other sections. Section 4 experienced the largest standard deviation of travel times, 35.08 and 36.37, for both the pre-improvement and intermediate improvement periods, respectively.

To fully grasp the increases in link travel times, the volume results must be incorporated into the travel time information. Table 4.7 summarizes the analysis results of the four link sections and combines the link travel time results with the volume results. Therefore, each counter location in the volume study was paired with each link section in the travel time study (e.g., Counter 1 – Link Travel Time Section 1).

Table 4.7 Link Travel Time Summary Table

	Amount of Peak Periods w/ Significant Increases in Volume	Before Travel Time		After Travel Time		Analysis				
		μ_B (sec)	σ_B (sec)	μ_A (sec)	σ_A (sec)	f-value	R^2	p-value	Significance?	Incr/ Decr in Travel Time
Section 1	4 (1NB/3 SB)	53.31	22.35	59.58	28.27	1.89	0.056634	0.1317	No	NA
Section 2	2 (1 NB/ 1 SB)	45.90	22.34	63.64	36.47	9.88	0.178967	**<.0001**	**Yes**	Increase
Section 3	0	53.70	29.00	60.63	33.42	1.63	0.151106	0.1831	No	NA
Section 4	3 (2 NB/1 SB)	91.42	35.08	101.49	36.37	3.86	0.0921	**0.0097**	**Yes**	Increase

As previously stated, to theoretically best evaluate each set of traffic improvements, volume would need to stay constant across improvement periods. Since there were many statistically significant changes in volume as indicated in *Section 4.2.1*, it is necessary to evaluate the volume analysis with the travel time analysis. Section 1 experienced the most peak periods with a statistically significant increase in volume, yet no statistically significant change in travel time occurred. The largest statistically significant increase in travel time occurred at Section 2, where an increase in volume only occurred during the northbound midday peak and the southbound PM peak. Because of the close proximity of the intermediate improvements to Section 2, it is more likely that the improvements were the direct cause of the significant increase in mean travel time. Section 3 seemed to be the least affected area, since it experienced no statistically significant increases in volume or travel time across the two collection periods. Section 4's statistically significant increase in mean travel time may be able to be attributed to the three peak periods with significant increases in volume (e.g., northbound midday, northbound PM, and southbound PM). To further examine these three cases, individual t-tests were performed to evaluate the changes in travel times for the three peak periods in question. The results of the 3 t-tests for Link Section 4 are shown in Table 4.8.

Table 4.8 Travel Time t-tests for Link Section 4 during Peak Periods with Statistically Significant Increases in Volume

Peak Period	μ_B (sec)	μ_A (sec)	σ_B (sec)	σ_A (sec)	t-value	Equal Variances	p-value	Significance?
NB Midday	91.23	107.30	32.32	31.02	1.81	Yes	0.0758	No
NB PM	105.57	121.13	45.71	39.22	1.3	Yes	0.1988	No
SB PM	86.68	110.70	31.35	39.36	2.2	Yes	**0.0323**	**Yes**

Note: μ = mean travel time (sec);
σ = standard deviation of travel time;
B= Pre-improvement conditions (Collected 3/29/10 – 4/2/10);
A= Intermediate Improvement Conditions (Collected 4/4/11 – 4/8/11)

The results shown in Table 4.8 indicate that out of the three peak periods in Link Section 4 that experienced a statistically significant increase in travel time, only the southbound PM peak period experienced a statistically significant increase in travel time. A p-value of 0.0323 was computed using a standard t-test. Therefore, only the southbound PM peak period's increase in travel time could be attributed to an increase in volume. The scope of the study does not allow for any further analysis into understanding how much of the increase in travel time for the southbound PM peak period was caused by the increase in volume or by the changes in the roadway landscape based on the intermediate improvements. Additionally, the northbound midday and PM peak periods did not experience statistically significant increases in travel time. Therefore, since none of the increases in travel time for these two peak periods were statistically significant according to the t-tests shown in Table 4.8, the statistically significant increase in volume during these peak periods did not significantly affect the travel time results for the peak periods in question.

4.2.3.2 Amount of Time Spent in Congestion or Stopped

Another effective measure of traffic analysis for both users of the system and traffic controllers is the amount of time spent in congestion. For this particular study, since the speed limit is 25 mph, the amount of time spent in congestion was selected as every second spent travelling under 10 mph based on the reviewed literature (Hutton, Bokenkroger et al. 2010). The same Visual Basic code that was used to calculate total and link travel times was used to calculate the amount of time spent travelling under 10 mph during each travel time run. This number was then divided by the total travel time for each run to give the percentage of time spent in congestion for each run. The mean times and percentages of time spent in congestion for each peak period are shown in Table 4.9.

Table 4.9 Results of Time and Percentage of Time Spent in Congestion (< 10 mph) Analyses

	Time Spent Travelling < 10 mph					% Time Spent Travelling < 10 mph					
Peak Period	μ_B (sec)	μ_A (sec)	t-value	p-value	Sig?	Avg % of Time Spent Before	Avg % of Time Spent After	Difference in %	t-value	p-value	Sig?
Northbound											
AM	87.4	103.2	1.21	0.23	No	41.2	40.0	-1.2	-0.23	0.8162	No
Midday	114.6	159.2	2.45	**0.0182**	**Yes**	51.2	58.8	7.6	1.04	0.305	No
PM	159.6	202.5	1.3	0.1994	No	67.4	66.6	-0.7	-0.07	0.9462	No
Southbound											
AM	74.2	106.3	2.47	**0.0175**	**Yes**	33.9	41.7	7.8	1.76	0.0841	No
Midday	101.7	117.4	1.01	0.3193	No	40.6	38.9	-1.7	-0.32	0.7495	No
PM	114.2	135.0	1.17	0.2498	No	40.1	39.1	-1.0	-0.19	0.8518	No

Note: Negative amounts in the % difference column indicate that a decrease occurred in the amount of time spent in congestion.

While this study largely mirrored the travel times study, its results can give different insights into the effects of the intermediate improvements. Overall, a slight decrease in the amount of time spent in congestion occurred. For the entire corridor, 4 of the 6 peak periods tested experienced a decrease in time spent in congestion. The largest rise, 7.8% more time, occurred during the Southbound AM peak period. Interestingly, vehicles travelling northbound spent a much longer amount of time on average than those travelling southbound during each peak period. Approximately half the time spent by drivers travelling northbound on the roadway during peak hours is spent travelling under 10 mph, which is under 50% of the speed limit. This result is not reflected in the travel time or volume studies.

t-tests, similar to those conducted in the speed analyses, were used to determine whether any statistically significant changes occurred across improvement periods in both the time and percentage of time spent in congestion results. Only the northbound midday peak and southbound AM peak experienced statistically significant changes in the amount of time spent in congestion (i.e., both experienced increases). It should be noted that both of these peak periods experienced increases in mean travel time (i.e., travel times for individual peak periods were not individually evaluated for statistical significance.). The northbound midday peak period experienced an average increase in total travel time of 37.7 seconds, from 259.6 seconds to 297.3. The southbound AM peak period experienced an average increase in total travel time of 40.7 seconds, from 213.4 seconds to 254.1 seconds across improvement periods. However, neither of the aforementioned peak periods along with any of the other peak periods tested experienced a statistically significant change in the percentage of time spent in congestion. Therefore, for both the peak periods that experienced statistically significant increase in amount of time spent in congestion, there associated total travel times for each travel run were large enough to keep the percent time spent in congestion averages from being statistically significant. Since evaluating the percentage of time spent in congestion uses the total travel time for each run, the measurement is able to stand alone apart from the travel time and speed studies.

To further examine these findings, the amount of time spent stopped was evaluated. According to the literature discussed in Section 2.3.1.3, the amount of time spent stopped should actually be evaluated as the amount of time travelling under 3 mph (Hutton, Bokenkroger et al. 2010). Table 4.10 shows the mean amount of time spent stopped in each direction for each peak period on the corridor. The same methods used to create Table 4.9 were used to create Table 4.10.

Table 4.10 Results of Time and Percentage of Time Spent Stopped (< 3 mph) Analyses

	Time Spent Travelling < 3 mph					% Time Spent Travelling < 3 mph					
Peak Period	μ_B (sec)	μ_A (sec)	T-Value	P-Value	Sig?	Avg% of Time Spent Before	Avg % of Time Spent After	Difference in %	t-value	p-value	Sig?
						Northbound					
AM	68.8	75.3	0.63	0.5281	No	32.5	29.2	-3.3	-0.8	0.4243	No
Midday	86.6	123.6	2.43	0.0192	**Yes**	38.5	45.6	7.1	1.16	0.2496	No
PM	117.3	154.6	1.42	0.1618	No	49.8	50.9	1.1	0.12	0.9042	No
						Southbound					
AM	56.8	75.3	1.9	0.0636	No	26.1	29.7	3.6	0.99	0.3287	No
Midday	75.4	85.4	0.77	0.4438	No	29.9	28.5	-1.5	-0.33	0.7459	No
PM	79.8	100.9	1.41	0.1654	No	27.8	29.5	1.7	0.38	0.7045	No

Note: Negative amounts in the % difference column indicate that a decrease occurred in the amount of time spent in congestion.

For directional breakdown results, the percentage of time spent stopped results largely mirror the percentage of time spent in congestion results. Vehicles travelling northbound experience more than 10% more amounts of time stopped during each peak period than vehicles travelling southbound do. However, largely different results occurred across the collection periods than in the congestion study. For example, the southbound AM peak, which experienced the most statistically significant increase in amount of time spent in congestion, did not experience a statistically significant increase in amount of time spent stopped. Therefore, the intermediate improvements may have indirectly led to increased congestion, but did not cause a significant increase in the amount of time spent in congestion during the southbound AM peak period. The only significant increase in amount of time spent stopped occurred across the northbound midday peak period. It appears that a large amount of the percent of time spent in congestion during the northbound midday peak was actually time spent stopped, since the two parameters overlap. It is also important to note that two of the four traffic counter locations, counter 2 and counter 4, experienced statistically significant increases in volume during the northbound midday peak. The increase in traffic demand probably influenced the rise in the amount of time spent stopped. As far as the analyses on percent of time spent stopped, none of the peak periods tested, including the northbound midday peak period, experienced a statistically significant change. Again, large increases in travel time greatly reduced the changes in percent of time spent stopped, thus resulting in no significant changes.

4.2.4 Summary of Results and Analyses

The overall effects of the intermediate improvements on the study corridor were largely predictable since the objective of most of the improvements was to improve pedestrian safety. The volume study experienced several peak periods with statistically significant rises in volume across improvement periods. These increases should be attributed to other compounding factors and are probably not a direct result of the intermediate improvements. However, there significant rise was noted and used in the speed and travel time results. The speed study largely correlated with the expected effects of the intermediate improvements. Counters downstream of the pedestrian improvements experienced statistically significant reductions in mean speed while upstream counters were unaffected or experienced slight increases in mean speed. Significant increases in volume did affect some of the speed results.

The travel time study experienced a statistically significant increase across the whole corridor. It was divided into four link sections to further evaluate the effects of the improvements on certain areas of the roadway. Of the four link sections, only Sections 2 and 4 experienced statistically significant increases in travel time. t-tests were performed on certain peak periods of section 4 to determine whether statistically significant increases in volume influenced the travel time results. To further supplement the travel time results, the percentage of time spent in congestion and percentage of time spent stopped was evaluated. The results largely mirrored the travel time study results with some minor exceptions. Vehicles traveling in the northbound direction experienced a much greater amount of time stopped or in congestion. Table 4.11 provides a more detailed summary of the results and analyses for all three major studies.

Table 4.11 Summary of Results and Analyses for the Intermediate Improvements

Field Study	Purpose of Study	Type of Analysis	Significant Results
Volume Study	To assess the changes in volume across each improvement period. The volume information also serves as a supplement to the two other studies by determining whether an increase/decrease in volume aided in significant changes in speed and travel time.	Volumes were aggregated into 8, 15-minute blocks per each peak period. Each block was averaged across all 5 days and paired with the corresponding block in another improvement period. A paired t-test was conducted in SAS to determine whether significant changes occurred across improvement periods.	• In both directions, 5 out of the 12 peak periods tested experienced significant changes in volume. • The PM peak period recorded the largest volumes and experienced a significant rise in volume for 6 out of 8 peak periods tested. • Only the southbound PM peak period at counter 3 experienced a significant reduction in travel time. • 4 peak periods recorded at counter 1 experienced significant increases in volume, a larger amount than any other counter location.
Speed Study	To asses changes in speed at midblock locations to determine the improvements effects on traffic throughput as well traffic calming for pedestrian safety	Speeds were collected using the same four traffic counters and pneumatic tube setups as the volume study. The choice of collecting at midblock locations was made so that free flow speeds would be collected.	• In the northbound direction, every peak period for counters 1, 2, and 3 experienced a significant change in mean speed. Counter 4 did not experience any significant changes. • In the southbound direction, 9 of the 12 peak periods recorded significant changes in mean speed. • Of the significant changes in speed, reductions occurred in the locations downstream from Section 2, where the intermediate improvements occurred. Increases occurred either upstream from the improvements or at counter 4, which is the farthest distance away from the campus core and the improvement locations.
Travel Time Study	To evaluate the changes in travel time across each improvement period in order to assess the overall effect of the improvements. Additionally, to further evaluate the improvements, the corridor was divided into four link sections.	Travel times were collected using the GPS test vehicle technique previously discussed in Section 2.2.2. During every peak period, 6 full corridor runs in each direction were made over 6 collection days. Position (latitude) and speed were collected at one second intervals as the vehicle traveled down the corridor.	• Using the nested ANOVA design, a significant increase in travel time occurred for the entire roadway across the improvement periods. • To further enhance the details, the nested ANOVA design was used to test four link sections of the roadway. Sections 2 and 4 experienced significant increases in travel time. Because all of the intermediate improvements were in close proximity to section 2, they were determined to be the major reason for the increase in travel time. • Additional t-tests were performed at counter 4 to determine if significant increases in volume caused significant increases in travel time. Only the southbound PM peak period experienced both significant rises in volume and travel time. • The results for percentage of time spent in congestion (<10mph) and amount of time spent stopped (<3mph) mostly reflected the travel time results. The northbound direction recorded higher percentages of time spent in congestion and stopped than the southbound direction.

Chapter 5: Conclusions and Recommendations

5.1 Introduction

The research in this report is focused on evaluating the effects of the improvements made to Donahue Drive on the Auburn University campus. The improvements included changes to both the traffic and pedestrian landscape on the signalized arterial that runs directly through the campus of Auburn University. The conclusion chapter focuses on evaluating the results of each set of analysis as well as assessing the overall effectiveness of the data collection and analysis methods. The conclusion sections are divided based on the three data collection techniques: the vehicular volume study, the speed study, and the travel time study. Recommendations for future research are included in Section 5.3.

5.2 Conclusions

Overall, the hypotheses made on the results of the intermediate improvement period were accurate. Because the main objective of most of the intermediate improvements was to improve pedestrian safety, it was expected that traffic flow would be adversely affected. This section includes conclusions made based on the results of the volume study, speed study, and travel time study.

5.2.1 Vehicular Volume

Vehicular volume was collected and analyzed as a supplement to the other traffic studies to ensure that changes in speed or travel time were not directly caused by an increase in traffic demand. Of the three peak periods studied at four locations, 5 of the 12 peak periods in each direction experienced statistically significant increases in volume. Overall, the PM peak period experienced the most statistically significant increases in volume from the pre-improvement period to the intermediate improvement period. Since the PM peak period already received the highest volumes, it is not surprising that significant increases would occur since data collection occurred over a year apart. Since a large amount of the peak periods tested experienced statistically significant changes, the changes were acknowledged in the speed and travel time studies. While no increase was expected, escalation in student enrollment and campus employment may have been an indirect cause of the increase in volume during many peak periods. Overall, changes to the study corridor have little to no influence on the amount of vehicles on the roadway, thus making it difficult to draw conclusions based on the volume study.

5.2.2 Speed Study

The speed study results gave a much greater means of evaluating the actual improvements than the volume study. The speed study results were able to be used in evaluating both traffic flow and pedestrian safety. As previously stated, a reduction in mean speed was expected across the intermediate improvement period since their main objective was to improve pedestrian safety. Overall, statistically significant reductions in speed occurred in locations that were closest to where the improvements were made. For example, since most of the improvements occurred in close proximity to counter 2, significant reductions in mean speed occurred at counter locations downstream of the improvements (e.g., at counter 1 in the southbound direction and at counter 3 in the northbound direction). Additionally, mostly significant reductions occurred at counter 2. Counter 4 experienced largely different speed results than the other counter locations because it is located farthest away from the campus core and is thus not subjected to as large of amounts of pedestrian volume as the other counter locations. Therefore, the intermediate improvements overall seemed to reduce speed as predicted. Because of the reduction in mean speeds, it may be concluded that pedestrian safety was improved for students walking to and from the campus core. Since pedestrian safety is nearly impossible to quantify in a short period of time, a reduction of mean speed in the areas closest to the improvements was the best way to positively grade the improvements effectiveness.

5.2.3 Travel Time Study

Travel time results were expected to increase across the intermediate improvement period based on the pedestrian nature of the improvements. Therefore, as expected, the analysis of the entire corridor resulted in a statistically significant rise in travel time across improvement periods. The nested ANOVA also indicated that the upper parameters of the hierarchy (i.e., direction and peak period) were statistically significant. To further explain the effects of the intermediate improvements, the nested ANOVA test was repeated on each of the Link Travel Time sections that corresponded with each of the four counter locations. Of the four Link sections, statistically significant changes (i.e., increases) only occurred at Section 2 and Section 4. Since Link Section 2 contains all of the intermediate improvements, the increase in mean travel time was attributed to the improvements as predicted. However, additional t-tests were conducted on Section 4 since the significant changes were unexpected. The t-test were conducted during peak periods that had experienced significant increases in volume from the previous study. All but one of the t-tests, the southbound PM peak period, did not experience statistically significant results in travel time. Since no changes were made in close proximity to Section 4, deducing a reason as to why the link section experienced a significant increase is difficult without a corresponding increase in volume. Perhaps train crossings skewed the travel time data during the intermediate improvement data collection period. Overall, the travel time study results were as predicted. The improvements caused travel time to rise across the entire corridor, especially in close proximity to their location.

The supplementary travel time studies used the travel time data to compute the amount and percentage of time spent in congestion (i.e., travelling < 10 mph) and time spent stopped (i.e., travelling < 3 mph). For both supplementary parameters, both the amount of time and percentage of time were analyzed to determine whether significant changes occurred across the intermediate improvement period. The results were largely similar to the results of the travel time analysis. Only two of the six peak periods tested experienced a statistically significant increase in amount of time spent in congestion, while only one peak period experienced an increase in amount of time spent stopped. However, none of the peak periods tested for either supplementary parameter experienced a statistically significant change in percent time spent. Since total travel time was a direct factor for the calculation of percent time spent in congestion and percent time spent stopped, the significant changes that occurred for amount of time spent in congestion and spent stopped were negated by the travel times. Therefore, percent of time spent in congestion and percent of time spent stopped were directly dependent on travel time. This parameter likely would be different if the signal coordination had occurred.

5.3 Recommendations for Further Research

The design of the methods for data collection and analyses was unable to be fully evaluated based on the nature of the intermediate improvements. Since the overall architecture of this study was supposed to deal with evaluating the corridor as a whole after a signal coordination and the addition of two new intersections, it would be unfair evaluate the data collection and analysis methods presented based on the intermediate improvement phase alone. Therefore, obviously after the final improvements are installed, data collection and analyses should occur similarly to the methods presented in Chapters Three and Four of this study. The final improvement results should indicate that the improvements affected traffic flow by reducing travel times while upholding existing pedestrian safety. After these results are documented, the overall data collection and analysis procedures should be evaluated.

Other recommendations for future research include performing a cost-benefit analysis on the improvements from a traffic flow perspective similar to the research by Chen and Park described in Section 2.3.1.1 (2010). This study could possibly give a greater insight into the effectiveness of making improvements to a signalized arterial with high pedestrian volumes. Other smaller future studies may be focused on the intersection of W Thach Ave and Donahue Drive. Observing and collecting pedestrian and vehicle behavior at the newly installed pedestrian signal could allow the new signal's effectiveness to be evaluated. Other options such as an above grade pedestrian bridge or a below grade tunnel could also be weighed based on cost and effectiveness.

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Appendices

Appendix A: Procedures for Determining the Amount of Vehicle Runs per Collection Period

Appendix B: Sample SAS® Codes for Analyses

Appendix C: Visual Basic Code for Computing Travel Times Information

Appendix A

Procedures for Determining the Amount of Vehicle Runs per Collection Period

This procedure is represented by the following equation:

$$R = \frac{S}{N-1}$$

Example:

APPROXIMATE MINIMUM SAMPLE SIZE REQUIREMENTS FOR TRAVEL TIME AND DELAY STUDIES WITH CONFIDENCE LEVEL OF 95.0 PERCENT					
Average Range in Running Speed (mph)* R	Minimum Number of Runs for Specified Permitted Error				
	± 1.0 mph	± 2.0 mph	± 3.0 mph	± 4.0 mph	± 5.0 mph
2.5	4	2	2	2	2
5.0	8	4	3	2	2
10.0	21	8	5	4	3
15.0	38	14	8	6	5
20.0	59	21	12	8	6
*Interpolation should be used when R is other than the numbers shown in column 1.					

Run #	**RS**	**Absolute Difference**
1	**38**	**0**
2	**35**	**3**
3	**32**	**3**
4	**33**	**1**
5	**36**	**3**
		10 (Total = S)

$$R = \frac{S}{(n-1)} = \frac{10}{(5-1)} = 2.5$$

where

RS = average running speed in mph
R = average range in running speed in mph
S = sum of absolute differences
N = number of completed test runs

Appendix B

Sample SAS® Codes for Analyses

Paired t-test for Vehicular Volume Analysis

```
data SBpairedAMct1;
        input Before After;
datalines;
88      91
93      93
68      59
52      60
68      62
67      77
52      43
45      46
50      55
91      95
95      88
56      80
58      61
38      33
52      62
72      68
60      72
44      49
108     77
98      70
60      70
63      67
64      69
58      86
52      38
58      53
60      62
87      101
101     85
60      59
63      50
52      49
58      54
69      70
55      59
```

```
45      50
95      103
100     108
55      78
45      80
47      77
50      92
31      64
40      55
58      68

;
proc print data = SBpairedAMct1;
run;
proc ttest data = SBpairedAMct1;
        paired before * after;
run;
```

Two-Sided t-test for Speed Analysis (A large portion of the dataset has been omitted)

```
data Ctr1SBAM;
        input speed period$;
datalines;
24      Before
19      Before
22      Before
23      Before
22      Before
32      Before
19      Before
19      Before
20      Before
30      Before
19      Before
18      Before
22      Before
21      After
28      After
25      After
14      After
14      After
13      After
14      After
17      After
19      After
28      After
25      After
26      After
22      After
;
proc ttest data = Ctr1SBAM;
        class period;
        var speed;
run;
proc univariate data = Ctr1SBAM;
        var period speed;
run;
```

Nested ANOVA for Travel Time Analysis (A large portion of the dataset has been omitted)

```
data TTtext1Sect1;
       input  Direction$ TOD$ Period$ TT;
datalines;
Northbound      Morning Before  45
Northbound      Morning Before  28
Northbound      Morning Before  71
Northbound      Morning Before  55
Northbound      Morning Before  66
Southbound      Morning Before  53
Southbound      Morning Before  55
Northbound      Morning After   140
Northbound      Morning After   64
Northbound      Morning After   36
Northbound      Morning After   36
Northbound      Morning After   59
Northbound      Morning After   56
Southbound      Morning After   65
Southbound      Morning After   75
Southbound      Morning After   45
Southbound      Morning After   61
Southbound      Morning After   62
Southbound      Morning After   86
;
proc print data = TTtext1Sect1;
run;
proc glm;
       class Direction TOD Period;
       model TT = Direction TOD(Direction) Period(TOD);
run;
```

Appendix C

Visual Basic Code for Computing Travel Times

```
Private Sub CommandButton1_Click()
Dim n As Integer, Segment_1 As Integer, Segment_2 As Integer, Segment_3 As Integer
Dim Segment_4 As Integer, i As Integer, j As Integer, latitude() As Double, speed() As Double,
uspeed() As Double
Dim under_10 As Integer, under_three As Integer

Segment_1 = 0
Segment_2 = 0
Segment_3 = 0
Segment_4 = 0
under_10 = 0
under_three = 0
n = Cells(1, 16)

ReDim latitude(n) As Double, speed(n) As Double, uspeed(n) As Double


For i = 2 To n
    latitude(i) = Cells(i, 4)
    If latitude(i) >= 32.5975 And latitude(i) <= 32.60103 Then Segment_1 = Segment_1 + 1
    If latitude(i) > 32.60103 And latitude(i) <= 32.60399 Then Segment_2 = Segment_2 + 1
    If latitude(i) > 32.60399 And latitude(i) <= 32.60627 Then Segment_3 = Segment_3 + 1
    If latitude(i) > 32.60627 And latitude(i) <= 32.61089 Then Segment_4 = Segment_4 + 1
Next i

For i = 2 To n
    latitude(i) = Cells(i, 4)
    speed(i) = Cells(i, 14)
    If latitude(i) >= 32.5975 And latitude(i) <= 32.61089 And speed(i) <= 3 Then under_three =
under_three + 1
    If latitude(i) >= 32.5975 And latitude(i) <= 32.61089 And speed(i) <= 10 Then under_ten =
under_ten + 1

Next i

Cells(4, 16) = Segment_1
Cells(4, 17) = Segment_2
Cells(4, 18) = Segment_3
Cells(4, 19) = Segment_4
Cells(4, 20) = Segment_1 + Segment_2 + Segment_3 + Segment_4
Cells(6, 16) = under_ten
Cells(6, 18) = under_three

End Sub
```