ARTERIAL PERFORMANCE AND EVALUATION USING BLUETOOTH AND GPS DATA

A Thesis

by

BRIAN THOMAS SHOLLAR

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Yunlong Zhang
Committee Members,	William Eisele
	Clifford Spiegelman
Head of Department,	John Niedzwecki

December 2012

Major Subject: Civil Engineering

ABSTRACT

Accurate travel time data are necessary to monitor and evaluate traffic conditions effectively. In the past 20 years, the hours per year lost by the average driver have increased by 300% in the 85 largest U.S. cities, which translates into lost productivity and increased costs. State department of transportation (DOT) agencies and other government organizations need accurate travel time and speed information to better combat this congestion faced by motorists. In the past, ground truth travel time information was typically collected with probe vehicles using the “floating car” method. However, new methods using data collected from global positioning systems by private companies such as INRIX®, Navteq®, and TomTom® have emerged that allow travel time data to be obtained more cheaply and quickly. The *Urban Mobility Report* (UMR) has turned to these companies, specifically INRIX®, for calculating congestion indices across the United States. This is done by analyzing average speeds and reference speeds supplied by INRIX.

The UMR analysis relies on INRIX-supplied reference speeds to calculate delay, which produces artificially high delay on many suburban arterials. Currently, these reference speeds are determined by taking the 85^{th} percentile of weekly speeds (typically overnight hours [10PM to 6AM]). There is a need to refine the reference speeds on arterials in order to account for signal operations, particularly during the daytime hours, so that the UMR more accurately reflects arterial congestion across the nation. Using Bluetooth and INRIX speed data, this thesis develops a new reference speed methodology that accurately reflects arterial delay during daytime hours. This study found that a 60% daytime free-flow reference speed best represents arterial congestion.

Using *Highway Capacity Manual* (HCM) guidelines, this thesis also explores the use of Bluetooth data for arterial and intersection level of service (LOS) analysis under both HCM 2000 and HCM 2010 methodologies. Through analysis, it was found that Bluetooth data capture more of the high and low LOS values compared to the HCM methodology based on segment speed calculations. These high and low LOS values, as well as the rapidly changing LOS between 15-minute intervals, could be attributed to an insufficient sample size.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

1. INTRODUCTION

It is important to have accurate travel time information in order to monitor and evaluate traffic conditions effectively. In the past 20 years, the hours per year lost by the average driver have increased by 300% in the 85 largest U.S. cities (*1*). This translates into lost productivity and increased costs. State departments of transportation (DOTs) and other government organizations need accurate travel time and delay information to better combat congestion faced by motorists.

Historically, travel time studies were conducted mostly on freeways. However, due to increased congestion levels on arterials, there is now a need for arterial travel time studies in both major and mid-sized cities. Arterial travel time data collection poses new challenges compared to freeway collection. One major challenge is the impact of traffic signals, which requires better data filtering than that needed in freeway travel time studies. In the past, ground truth travel time information on arterials was often collected with probe vehicles using the "floating car" method. This method of collection involves sending out drivers who record how long it takes to travel from one reference point, such as a busy intersection, to the next reference point.

This is usually done on major arterials during peak periods using a stop watch and recording the time by hand or, more recently, by attaching a global positioning system (GPS) antenna to the vehicle.

Emerging technologies such as Bluetooth and GPS enable engineers and planners to determine vehicle travel times quickly and at a relatively low cost. These technologies can be used to measure delay, determine level of service (LOS), and evaluate signal operations. Many modern cell phones and in-vehicle entertainment systems are now Bluetooth-equipped and emit a Bluetooth signal when in discovery mode. This Bluetooth signal can be collected using receivers placed on the sides of roads to track the progression of the Bluetooth signal along a corridor.

GPS data are collected by private companies such as INRIX®, Navteq®, and TomTom® . These companies aggregate data from taxis, airport shuttles, service delivery vans, long haul trucks, consumer vehicles, and GPS-enabled consumer smart phones. The data collected include the speed, location, and heading of a particular vehicle at a reported date and time (*2*). Both Bluetooth and GPS technologies are fairly new and require validation and application, particularly for arterial operations.

Travel time estimation is important on arterials, not only for assessing the congestion level, but also for evaluating the performance of signal timing and coordination on arterials. Bluetooth and GPS technologies can also aid in properly assessing traffic signal operations.

1.1 PROBLEM STATEMENT

Signal progression or coordination is often employed on arterial corridors as a means of keeping traffic moving, and signals are often timed with respect to surrounding signals. Typically, signals are offset or delayed from an upstream signal by the time it takes a vehicle to travel from the upstream signal to the downstream signal. The intent of signal progression is to have vehicles move in groups, or platoons, down a corridor. When done properly, vehicles will leave an upstream signal during the green phase, and the downstream signal will begin the green phase as the vehicles approach the intersection. This allows for fluid movement down the corridor, with limited vehicle deceleration. However, improperly timed signals can cause traffic flow issues such as vehicles encountering multiple red lights in series, or lengthy vehicle queues upstream. Improperly timed signals can cause a reduction in free-flow speed (FFS) and level of service, while a properly configured signal system can greatly improve traffic flow characteristics. Traffic engineers need to know when such problems arise along a corridor, and typically discover them through data collection.

Bluetooth technology is widely accepted for freeway data collection. However, this technology and its usefulness on arterial operations has not been tested as extensively. Arterial operations present additional hurdles that this technology must overcome such as sink nodes between two detectors and low read rates. Sink nodes are destinations that motorists tend to make brief stops at such as gas stations or coffee shops. These stops add artificial travel time between the two readers as the stopped time is recorded as part of the travel time. There is a need to verify that Bluetooth technology is reliable in this application. This involves analyzing the Bluetooth data on multiple arterial corridors with varying characteristics and comparing the results to different technologies such as GPS collection.

There is also a need to investigate the difference between freeway analysis and arterial analysis. Both methods rely on reference speeds to calculate delay. Delay is calculated based on INRIX-supplied reference speeds, which are producing artificially high delays on many suburban arterials, to the point that some arterial roads are showing higher congestion than some of the worst congested freeways in the country. Currently, these reference speeds are determined using 24-hour speed data and applied for the whole day. This is acceptable for freeway analysis as freeways operate under primarily uninterrupted flow. However, arterials operate under interrupted flow due to signal operations. These signal operations vary based on time of day and direction of flow and can have a significant impact on travel speeds, and therefore the congestion index. There is a need to refine the reference speed on arterials in order to account for signal operations, particularly during daytime peak periods. Using Bluetooth and INRIX speed data, a new reference speed needs to be developed that accurately reflects arterial delay during peak periods.

The *Highway Capacity Manual* (HCM) 2000 (*3*) level of service for arterials is based on travel time. The data collected by Bluetooth or GPS can be used to assess the LOS of an arterial. This study intends to validate the HCM arterial procedure using Bluetooth data. Arterial level of service will be determined using the old and new HCM methods and compared as a practical planning application of the HCM methods (*3,4*). This arterial LOS will be compared to the intersection LOS to investigate the relationship between them. The intersection LOS can also be determined using Bluetooth data. Using these results, the quality of signal operations will be assessed.

1.2 OBJECTIVES

The goal of this research is to evaluate, refine, and validate the use of Bluetooth and GPS technology for travel time and delay data collection on arterial corridors, as well as to improve analysis procedures for the *Urban Mobility Report* (UMR) (*5*) and to evaluate arterial corridors using Bluetooth data.

The research objectives are:

- Compare travel times from Bluetooth and GPS. The advantages and disadvantages of these data sources will be analyzed and discussed in later sections.

- Refine the INRIX reference speed methodology to be used in mobility analysis in order to assess delay and operational performance.

- Explore the differences between arterial reference speeds and freeway reference speeds.

- Use Bluetooth data to assess and compare arterial LOS and intersection LOS.

- Use Bluetooth data to justify the new HCM methodology and compare the HCM 2000 (*3*) LOS methodology to the HCM 2010 (*4*) LOS methodology using a practical application of HCM methods.

2. BACKGROUND

There has been extensive study into the implementation and analysis of Bluetooth readers and GPS probe vehicles, and those studies are addressed in this thesis.

2.1 BLUETOOTH

Bluetooth is an Institute of Electrical and Electronics Engineers (IEEE) standard used for short-range wireless communication between devices. Most cell phones incorporate Bluetooth technology, as well as some GPS units and modern car entertainment systems. Because of its widespread use, Bluetooth tracking gives officials the ability to collect a larger portion of vehicle movements than traditional methods. Bluetooth is implemented by placing receivers on the side of the road to track the progression of the Bluetooth signal along a link or corridor. These collected data can then be used to determine travel time and travel speed data. An illustration of a Bluetooth traffic monitoring system can be found in Figure 1.

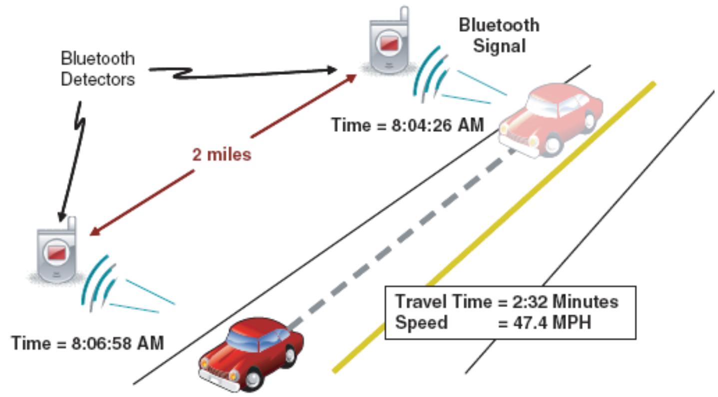

FIGURE 1 Bluetooth traffic monitoring operation concept (*1*).

A successful Bluetooth data collection is dependent on the placement of the receivers and the hardware used. Bluetooth reader placement is dependent on whether the application is for short-term data collection or for permanent continuous data collection. If only short-term data collection is needed, Bluetooth readers can be placed along the roadway in weather-resistant cases that include a portable battery (*6*). When this type of collection is used, the data collected from the receiver are usually stored locally as no network connection is available and the data have to be retrieved manually, usually at the end of the study. One of these portable readers can be seen in Figure 2.

FIGURE 2 Portable Bluetooth reader located in west Houston on TX-6 (*6*).

For a permanent data collection location, Bluetooth readers are usually installed in existing traffic signal cabinets. These cabinets are usually located at a signalized intersection. This location choice allows for a better understanding of link travel times to the public, but it can reduce the ability to accurately measure individual intersection delay, especially if other signalized intersections exist between adjacent Bluetooth readers. These signal cabinets are the preferred installation location because the cabinets offer weather protection, a power source, and sometimes an existing connection to the Traffic Management Center (TMC) – allowing for real-time monitoring of the Bluetooth system.

Bluetooth-enabled devices can communicate with other Bluetooth-enabled devices anywhere from approximately 3 feet to about 300 feet (*1*). The Bluetooth communication standard was designed to operate around obstructions, but real-world applications have found that Bluetooth read rates are consistently higher with a clear line-of-sight. As Bluetooth devices can be read anywhere within a 100 m radius of a reader, it is important that the spacing between readers is large enough to reduce the error to tolerable levels in relation to the overall link length. The placement of these readers is dependent on the road classification type. Researchers at the University of Maryland and the Texas Transportation Institute (TTI) concluded that a spacing of 1 to 2 miles for freeways is optimal, with a maximum spacing of 4 or 5 miles. For major arterial streets a spacing of 0.5 to 1 mile is optimal, with a maximum of 2 or 3 miles between Bluetooth readers (*7*).

As with other wireless probe tracking technologies available, travel time errors can be introduced in two ways: estimated spatial location of the probe, and route deviation. Estimated spatial location of the probe has historically been an issue with cell phone tracking technology, but is much less problematic with toll tag tracking. As the range of Bluetooth devices is comparable to that of toll tags, at only a few hundred feet of spatial error, this type of travel time error is not expected to be an issue. Researchers have found that the error associated with Bluetooth is relatively modest and is easily tolerable on larger segments (2 to 3 miles) (*8*).

Using standard time-distance calculations, the maximum expected error due to the location uncertainty of devices in the read radius can be determined by assuming the two extreme cases where the device is read at the fringe of the reading radius:

1. The Bluetooth device is read 100 m before the first reader, and 100 m after the second reader.
2. The Bluetooth device is read 100 m after the first reader, and 100 m before the second reader.

From Figures 3 and 4, it can be seen that as speeds get slower, the Bluetooth readers can be placed more closely together without appreciable increase in speed error (*7*).

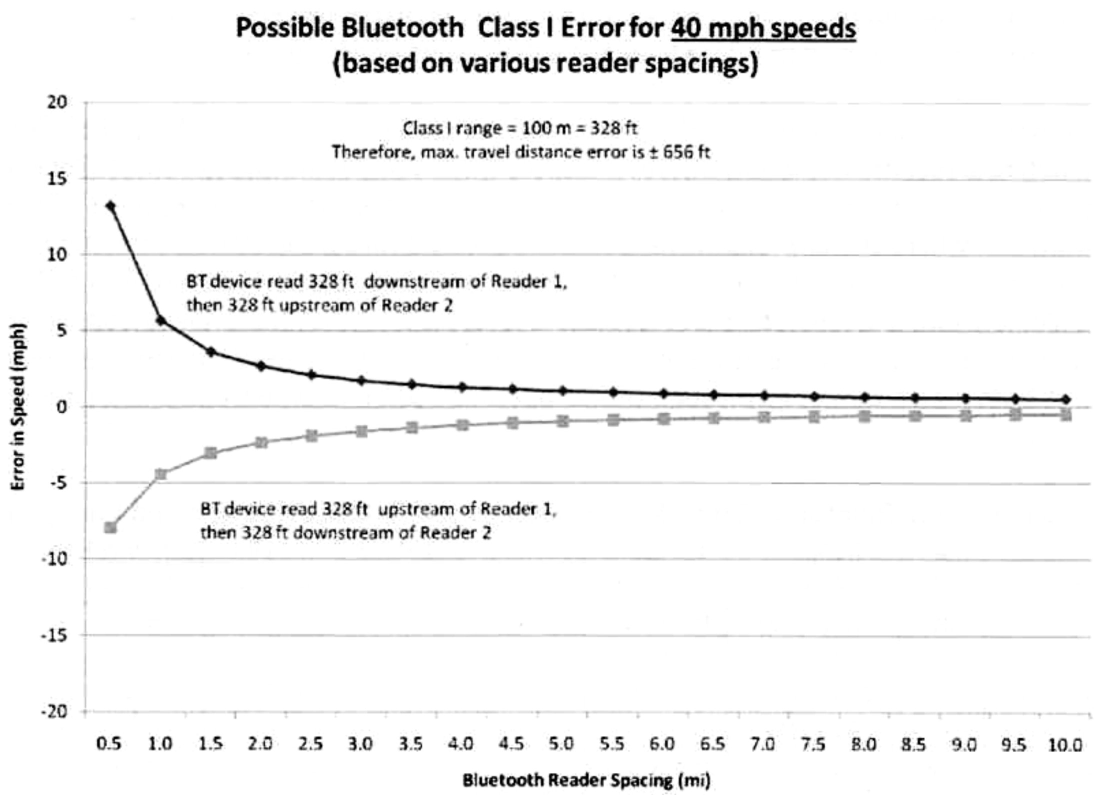

FIGURE 3 Maximum Bluetooth-based speed error at 60 mph due to location uncertainty (*7*).

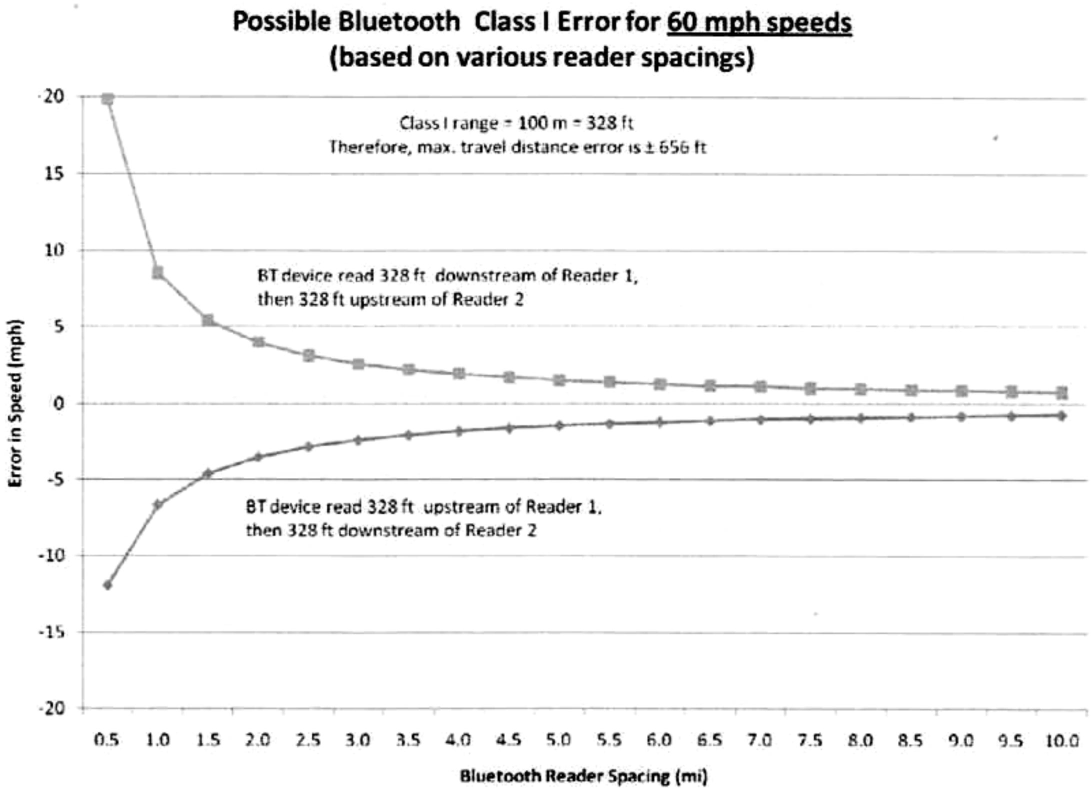

FIGURE 4 Maximum Bluetooth-based speed error at 40 mph due to location uncertainty (*7*).

The second way travel time error can be introduced is from subject vehicles deviating from the expected route. This is caused when the trip's origin-destination route does not follow the Bluetooth readers along the link or corridor. This error is usually addressed using a central tendency estimator, generally the modal travel time or a percentile, and is harder to combat on arterial streets than on access-controlled freeways (*8*).

On arterial streets, subject vehicles often make short stops for coffee or food, making estimating representative travel times more challenging. For quality control reasons, it is important to filter out these outliers when calculating average speed. Outlier identification algorithms depend on whether the average speeds are being calculated in real-time or from post-processing historical Bluetooth readings. Researchers at the University of Maryland have conducted detailed research (*1*,*9*) on outlier filtering during post-processing of historical reads. One example of real-time outlier filtering is the Houston toll tag-based traffic monitoring system, which uses the "acceptable buffer" algorithm. This algorithm compares each new toll tag match with the previous toll tag match (valid or invalid) on that link, and if the new match speed is greater than 20% higher or lower than the previous speed it is considered invalid (*7*). This system has been in use for about 15 years and has been proven to be accurate and successful. However, this system has been in use on freeways with controlled access, making it easier to identify vehicle detours and stops.

Previous research has proved that Bluetooth technology can reliably measure travel times on freeways. A vehicle probe project on the I-95 corridor observed an average detection rate of 2-3%. By analyzing the Bluetooth data collected from the I-95 project, researchers were able to observe traffic incidents and construction delays (*10*). In order to validate Bluetooth data on freeways, researchers at the University of Maryland carried out extensive floating car drive tests. The findings from these floating car tests indicated that Bluetooth travel times are quite accurate on freeway segments. The same study concluded that the accuracy of Bluetooth travel time estimates increases with the length of the road segment as well as the congestion level (*11*), whereas traditional traffic monitoring technologies begin to fail as congestion grows.

2.2 GPS

GPS data are collected by private companies such as INRIX (*12*). INRIX aggregates data from taxis, airport shuttles, service delivery vans, long haul trucks, consumer vehicles, and GPS-enabled consumer smart phones from consumers using the INRIX "Traffic!" app on the iPhone and Android, as well as from many of its mobile navigation customers. The data collected include the speed, location, and heading of a particular vehicle at a reported date and time (*2*). Using these probe vehicle reports, INRIX is able to establish a current estimate of travel patterns in all major cities in the United States as well as aggregate the data over periods of time for segments of roads. INRIX analyzes almost the entire limited access road network in the United States, spanning over 1 million miles (*12*). Since 2006, INRIX has been monitoring congestion across the nation and producing the INRIX National Traffic Scorecard series annually, where it publishes up-to-date information regarding overall congestion and specific bottlenecks across the United States (*2*). Figure 5 shows the roads analyzed by INRIX.

FIGURE 5 INRIX road network (*2*).

In order to aggregate data over periods of time, INRIX breaks roads into segments. These road segments are defined using an industry convention known as Traffic Message Channel codes, which are developed and maintained by electronic map database vendors. Typically, the road segment is defined as the intersection and the portion of linear road leading up to the interchange across all lanes in a single direction of travel, with the length of the segment varying depending on the distance between interchanges.

2.3 CURRENT UMR REFERENCE SPEED METHODOLOGY

Currently, the UMR analysis relies on INRIX-supplied reference speeds to calculate delay. These reference speeds are determined by taking the 85th percentile of the weekly speeds (typically overnight hours [10PM to 6AM]). This is acceptable for freeway analysis, as freeways operate under primarily uninterrupted flow. However, arterials operate under interrupted flow due to signal operations. These signal operations vary based on time of day and direction of flow and can have a significant impact on travel speeds, and therefore the congestion statistics.

Using this 85^{th} percentile reference speed from freeway applications does not transfer well to arterials. Arterials operate essentially as freeways during the overnight hours due to effective signal timings, as there is a substantially lower volume of cars queuing on cross streets at night, allowing for greater signal priority to the main arterial. However, as traffic increases during the daytime and traffic signal timing plans change, less green time is given to the main arterial, which results in interrupted flow. By applying freeway reference speed methodology to arterials, nighttime conditions are used that are not representative of those experienced by motorists during the day.

2.4 HIGHWAY CAPACITY MANUAL

The *Highway Capacity Manual* is published by the Transportation Research Board in the United States. The manual contains methodology for calculating the capacity and quality of service of different transportation facilities. The HCM was first released in 1950 and is continuously improved and updated. To date, there have been five editions of the HCM, with HCM 2010 being the most recent. As this version was recently released, most LOS calculations in this thesis were performed following the older yet more commonplace HCM 2000 procedures. There are substantial changes between the HCM

2000 edition and the HCM 2010 edition with respect to LOS calculations on arterials, and a comparison of these two methods is discussed in this paper.

2.5 SIGNAL PROGRESSION AND INTERSECTION LOS

The purpose of signal progression is to have vehicles move in groups, or platoons, down a corridor. When done properly, vehicles will leave an upstream signal during the green phase, and the downstream signal will begin the green phase as the vehicles approach the intersection. This allows for a fluid movement of vehicles down the corridor, with limited deceleration.

Signal progression or coordination is often employed on arterial corridors as a means of keeping traffic moving. Signals are timed with respect to surrounding signals. Ideally, greens on the main street in the through direction should be offset, or delayed, from the upstream signal by the time it takes a vehicle to travel from the upstream signal to the downstream signal to achieve the best possible coordination between signals. However, this ideal offset concept works only for one-way streets, and in practice there is substantial difficulty with two-way coordination. That is, offsets generally favor the direction with higher traffic volumes at the expense of the opposing direction. The reason for this difficulty is the fact that the offsets in two directions at any intersection add up to an integer multiple of the cycle length, hence they are not independent of each other.

When problems arise with coordinated signals, they can often cause havoc with traffic patterns. One such problem might involve vehicles encountering multiple red lights in series, which can frustrate drivers and cause confusion. In some situations, vehicles can even begin to queue back upstream, causing gridlock at upstream signals, which only worsens the situation. These issues are often caused by improperly coordinated signals or a drastic shift in traffic patterns. Therefore, it is crucial for traffic engineers to know when a problem arises along a corridor. Bluetooth readers can be installed cheaply and quickly in traffic signal cabinets at desired intersections in order to provide information to traffic engineers.

Traffic signal operations are often the determining factor in how well an urban arterial performs. Signals can help improve mobility and reduce congestion, but when they are not configured properly, they can cause negative effects on the arterial. Therefore it is important to have a quantitative method of identifying how a street is performing. The most commonly used and accepted method is the level of service method. LOS was first introduced in the 1965 edition of HCM. The level of service method uses a letter-grade system for characterizing the quality of operations on a variety of traffic facilities. The HCM has since been updated and revised throughout the years, with HCM 2010 being the most current manual. Chapter 15 of the HCM describes urban street LOS analysis, and uses urban street classifications and average travel speed along the arterial for determining the LOS of the street. This average travel speed includes the control delay of the through movements at signalized intersections. Therefore, an accurate estimation of delay at signalized intersections is an important factor in the analysis of urban arterials (*13*). Chapter 16 of HCM describes signalized intersections and uses control delay per vehicle as the measure of determining intersection LOS. Control delay is the delay introduced to a vehicle from the traffic signal.

Signal progression can have a dramatic effect on arterial LOS. The purpose of coordinating traffic signals is to provide smooth flow of traffic along streets and highways in order to reduce travel times, stops, and delay (*14*). These reductions result in improved LOS for the arterial and also reduce fuel consumption and improve air quality. However, there are many variables that can affect arterial progression performance. The main effects are caused by signal cycle length, signal spacing, and the phase sequence. These will not be analyzed in depth in this paper, but it is important to be aware of these variables when evaluating signal progression.

3. DATA

3.1 DATA COLLECTION

In this research, five different arterial corridors were analyzed. All of these corridors are located in the west Houston, Texas, area. Due to the availability and consistency of data, in some cases Bluetooth data points were combined over multiple segments using a weighted average (by distance) to match INRIX data segments. Conversely, some INRIX data points were combined and averaged using the same methodology to match up with Bluetooth reader locations in some instances. The corridors used in the analysis are listed in Table 1.

TABLE 1 Study Corridors

Road Name	**Western-most Point**	**Eastern-most Point**
Memorial Dr	Eldridge Pkwy	Blalock Rd
Briar Forest Dr	SH-6	Gessner Rd
Westheimer Pkwy	Eldridge Pkwy	Gessner Rd
Dairy Ashford Rd	Westheimer Pkwy (Southern-most Point)	Memorial Dr (Northern-most Point)
Richmond Ave	Gessner Rd	Chimney Rock Rd

GPS data were collected by INRIX using the methods previously discussed. These data were supplied by INRIX in 15-minute intervals and aggregated on a yearly basis. Bluetooth data were collected using Bluetooth readers that record the unique address of each Bluetooth device and were located at major intersections along the arterial corridors. These data were collected by TTI-Houston and the City of Houston in 15-minute intervals. TTI-Houston supplied the data, with a collection period between a month and a half, and a year and a half, depending on the segment. Wednesday aggregate Bluetooth data for the Westheimer corridor is shown in Figures 6 and 7 with 95% confidence intervals. There is substantially more jitter in the confidence intervals during the overnight hours.

Table 2 lists the segments that required multiple data points to be averaged to determine a common segment for the analysis.

TABLE 2 Combined Segments

Road Name	Bluetooth Segments (# Combined)	INRIX Segments (# Combined)
Memorial Dr	Dairy Ashford-Wilcrest (2)	Wilcrest-Blalock Rd (4)
Briar Forest Dr	Dairy Ashford-Wilcrest (2)	Wilcrest-Gessner (2)
Westheimer Pkwy	-	Wilcrest-Gessner (2)
Dairy Ashford Rd	-	-
Richmond Ave	-	-

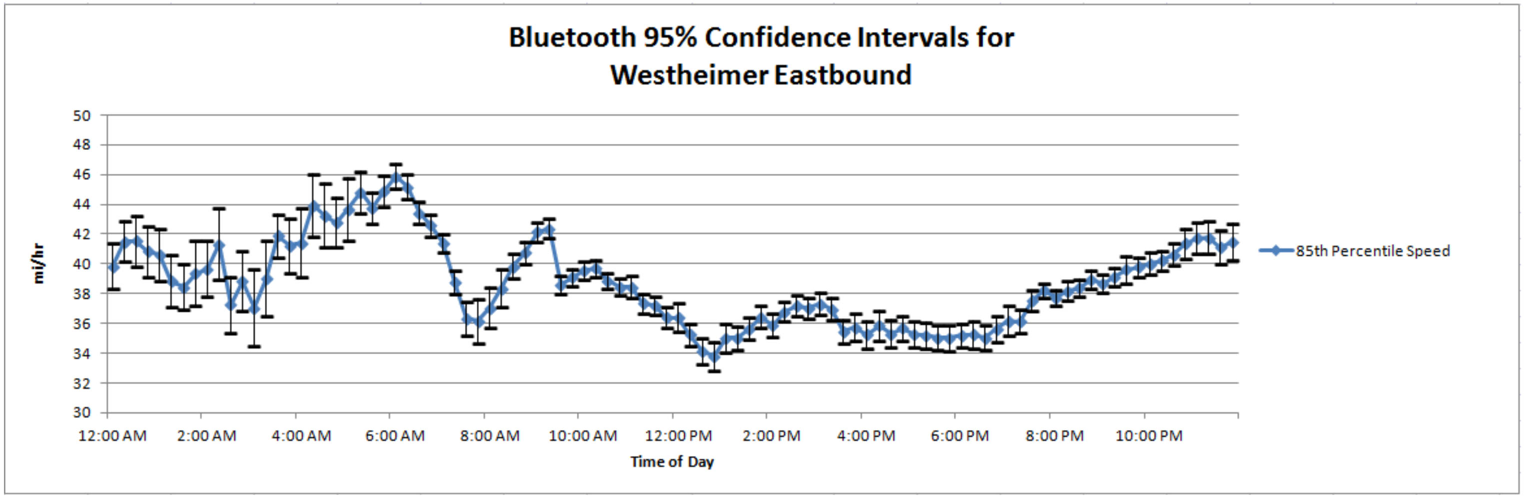

FIGURE 6 95% Confidence Intervals for Westheimer Eastbound.

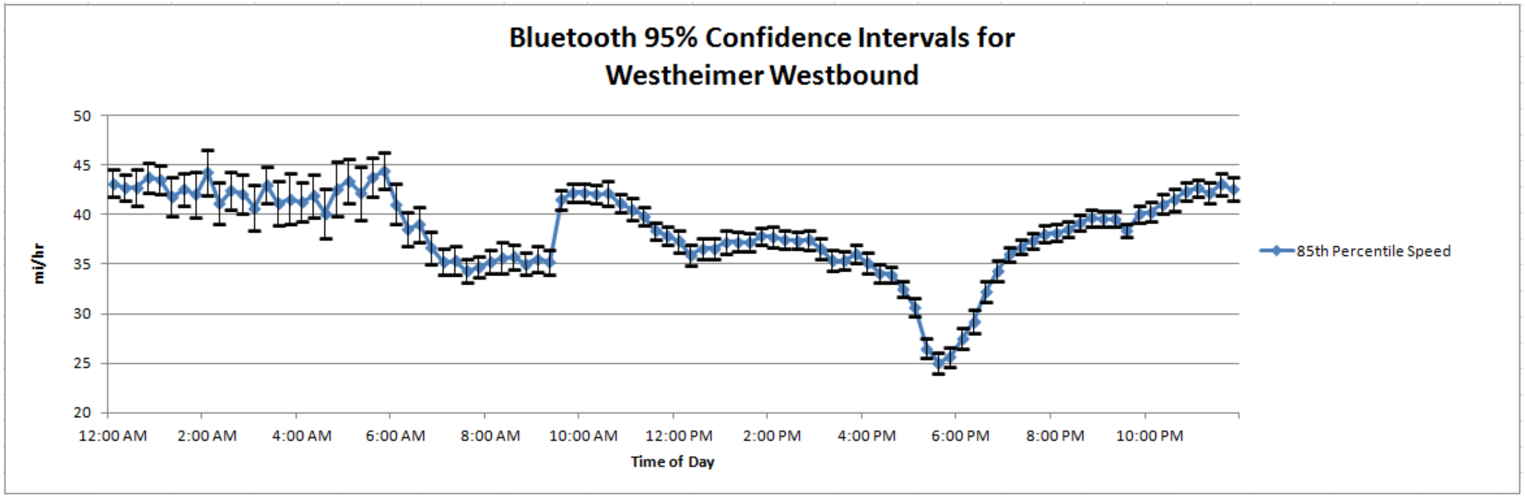

FIGURE 7 95% Confidence Intervals for Westheimer Westbound.

3.2 DATA FILTERING

For GPS data filtering, INRIX has developed its own proprietary methodology for filtering outliers. As part of the process, INRIX requires a minimum of four vehicle reads during a sample period before an average speed is reported for a segment.

TTI staff performed basic data filtering on Bluetooth data to remove sink node trips. Further filtering was applied using engineering judgment to remove artificially high travel times. From analyzing travel times for all of the segments in the study area, it was determined that an outlier was defined as a travel time exceeding 15 minutes for a segment, and outliers were discarded from the analysis. While timestamps were available for each Bluetooth data point, these data points were averaged into 15-minute “buckets” to conform to INRIX 15-minute intervals.

4. REFINING THE INRIX REFERENCE SPEED METHODOLOGY

4.1 REFERENCE SPEEDS

Refining the reference speeds for the mobility analysis required a comparison between the Bluetooth and GPS data in order to verify the quality of the datasets. An initial difference in the datasets was found in the depth of the data. While Bluetooth data were collected in real-time and time stamps were provided, INRIX data were provided in pre-grouped 15-minute buckets. This did not allow researchers to perform further data filtering on the INRIX data, as individual data points were unavailable. While INRIX requires a minimum of four data points within a 15-minute period before it will report a speed, the Bluetooth data were considered even when only a single data point was available. However, it is important to consider that INRIX data were collected over the entire year, while the Bluetooth collection period was substantially shorter, resulting in possibly fewer data points for certain time periods. This could result in over valuing single Bluetooth data points, therefore it was important to consider more than just a 15-minute time period.

While Bluetooth data were typically available for most of the day, INRIX data were available only for daytime periods in most cases. This is most likely due to INRIX's collection methods, which rely heavily on commercial fleet vehicles that operate during daytime business hours. The heavy reliance of the INRIX data on fleet vehicles should also be considered when analyzing the speed data. Commercial fleet vehicles are typically larger trucks that have slower acceleration and deceleration times and require larger vehicle headways, which could result in artificially lower travel speeds. Bluetooth data are typically collected from motorist's cell phones, which better represents the majority of vehicles on the road and current traffic conditions.

Currently, the UMR analysis relies on INRIX-supplied reference speeds to calculate delay. These reference speeds are determined by taking the 85^{th} percentile of the weekly speeds (typically overnight hours [10PM to 6AM]). This is acceptable for freeway analysis, as freeways operate under primarily uninterrupted flow. However, arterials operate under interrupted flow due to signal operations. These signal operations vary based on time of day and direction of flow and can have a significant impact on travel speeds, and therefore the congestion statistics. By applying freeway reference speed methodology to arterials, nighttime conditions are used that are not representative of those experienced by motorists during the daytime.

A variety of techniques were explored to develop a suitable methodology of determining an accurate reference speed. Currently, INRIX supplies a single reference speed for the entire day for each road segment. All of the proposed methods studied the possibility of using a daytime reference speed and a nighttime reference speed. In order to determine accurate daytime and nighttime periods, signal timing plans were provided by the TTI-Houston office. As it is not possible to retrieve this type of data on a national scale, these signal timing data were used along with Bluetooth and INRIX data to see if there was a broadly applicable and analytical approach to define daytime and nighttime periods.

After discussion with INRIX staff, it was found that the INRIX reference speed calculation is based off of the 85th percentile of the weekly speeds. It was decided that a daytime variation of the 85th percentile should be considered as a possible new reference speed to better reflect the congestion seen on the arterial corridors. Two corridors in west Houston, Westheimer from SH-6 to Chimney Rock and Dairy Ashford from Westheimer to Memorial, were chosen for further analysis. Using Bluetooth data as the ground truth data, two methods were devised to determine the beginning and end of this daytime period.

The first method uses the equation $\frac{Standard\ Deviation\ for\ Each\ Hour}{24\ Hour\ 85th\ Percentile} \leq X$. This equation was graphed with time on the x-axis and the value 'X' on the y-axis. Using these graphs, a value was determined that resulted in start/end points that generally occurred at the signal timing plan changes.

From the signal timing plans, it was found that the AM peak signal timing begins at 6:00AM. From the plots in Figures 8 and 9, a $\frac{Standard\ Deviation\ for\ Each\ Hour}{24\ Hour\ 85th\ Percentile} \leq X$ value of ~0.12-0.14 was found at approximately 6:00AM. It can be seen that the $\frac{Standard\ Deviation\ for\ Each\ Hour}{24\ Hour\ 85th\ Percentile} \leq X$ values are lower during the nighttime (off-peak) periods and begin to increase during the morning peak period, with a noticeable increase in the $\frac{Standard\ Deviation\ for\ Each\ Hour}{24\ Hour\ 85th\ Percentile} \leq X$ values between the 5:00AM and 6:00AM data points. Using these findings, it was determined that the daytime peak period begins when a value of 0.13 is reached.

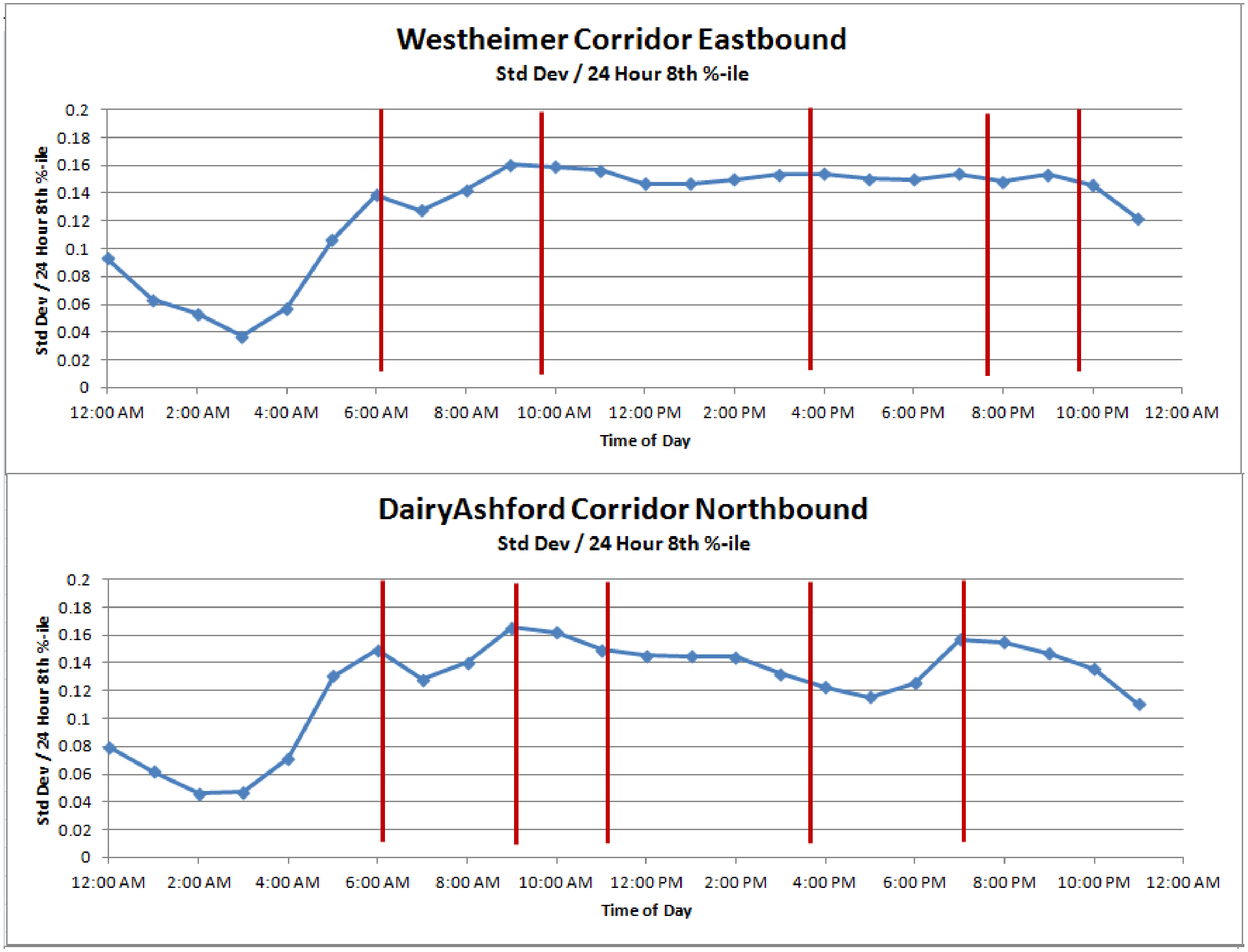

FIGURE 8 Method 1 corridor plots (EB and NB).

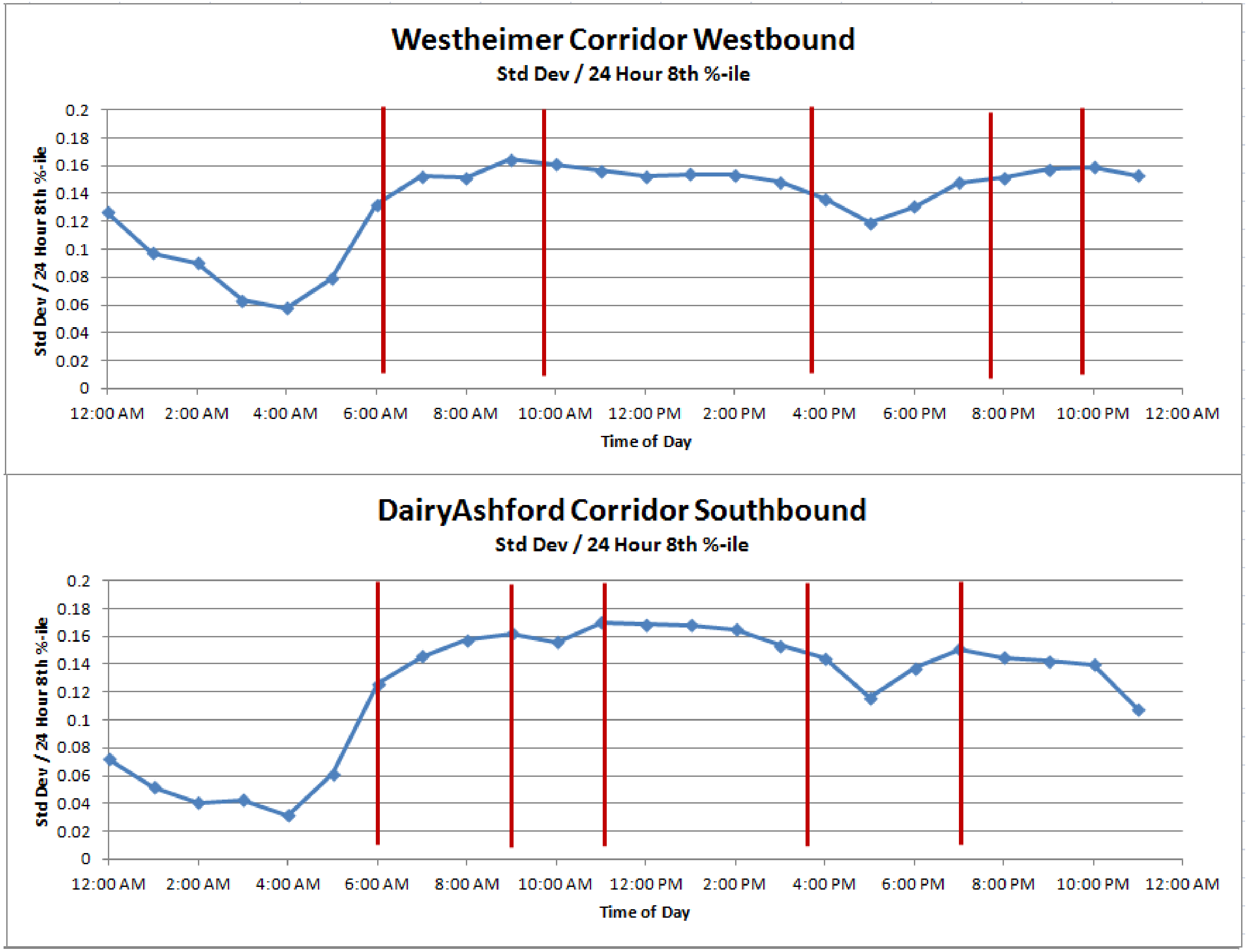

FIGURE 9 Method 1 corridor plots (WB and SB).

The PM peak signal timing plan is active from 3:30PM-7:30PM (7:00PM for Dairy Ashford). Both the Westheimer westbound and Dairy Ashford southbound plots show a decrease in the ratio value around 5:00PM, but these two corridors experience heavy PM volumes and this decrease is not as prevalent in the opposing directions. A possible cause for this decrease might be due to the initial inefficiency of the PM timing plan. As volumes become similar to design values for the PM timing plan, the values begin to increase again as real-world conditions begin to match the design parameters. Another possible explanation is that this dip might represent where the PM peak ends and where the evening home-based trips begin. However, from discussions it has been determined that the former explanation is more plausible. For this analysis, it was determined that the daytime 85th percentile would end where the $\frac{Standard\ Deviation\ for\ Each\ Hour}{24\ Hour\ 85th\ Percentile} \leq X$ value was the lowest between 4:00PM and 8:00PM. If this method were to be explored in more depth, this end point might be shifted to an hour or more after the lowest value.

The second method compared the 24-hour 85th percentile to each hourly 85th percentile and determined where they started to differ. The hourly 85th percentile minus the 24-hour 85th percentile was plotted with time on the x-axis, and the difference on the y-axis and can be found in Figures 10 and 11. From these plots, it was seen that the hourly 85th percentile usually began to decrease between 6:00AM and 7:00AM, which coincides with the timing plan changes at 6:00AM. Therefore, the daytime 85th percentile was determined to be from the first negative (in AM peak) hourly minus 24-hour 85th percentile until last negative hourly minus 24-hour 85th percentile (in PM peak).

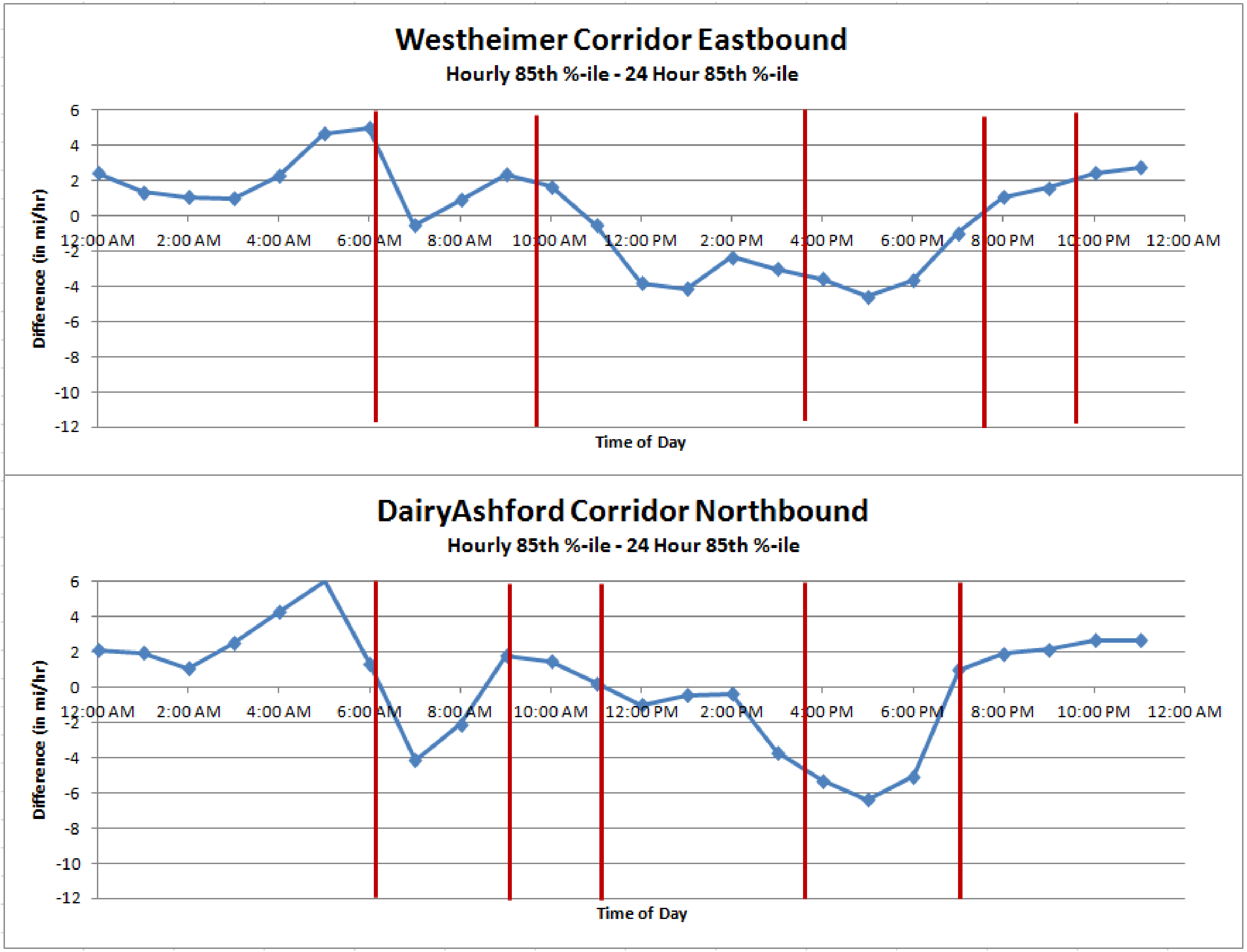

FIGURE 10 Method 2 corridor plots (EB and NB).

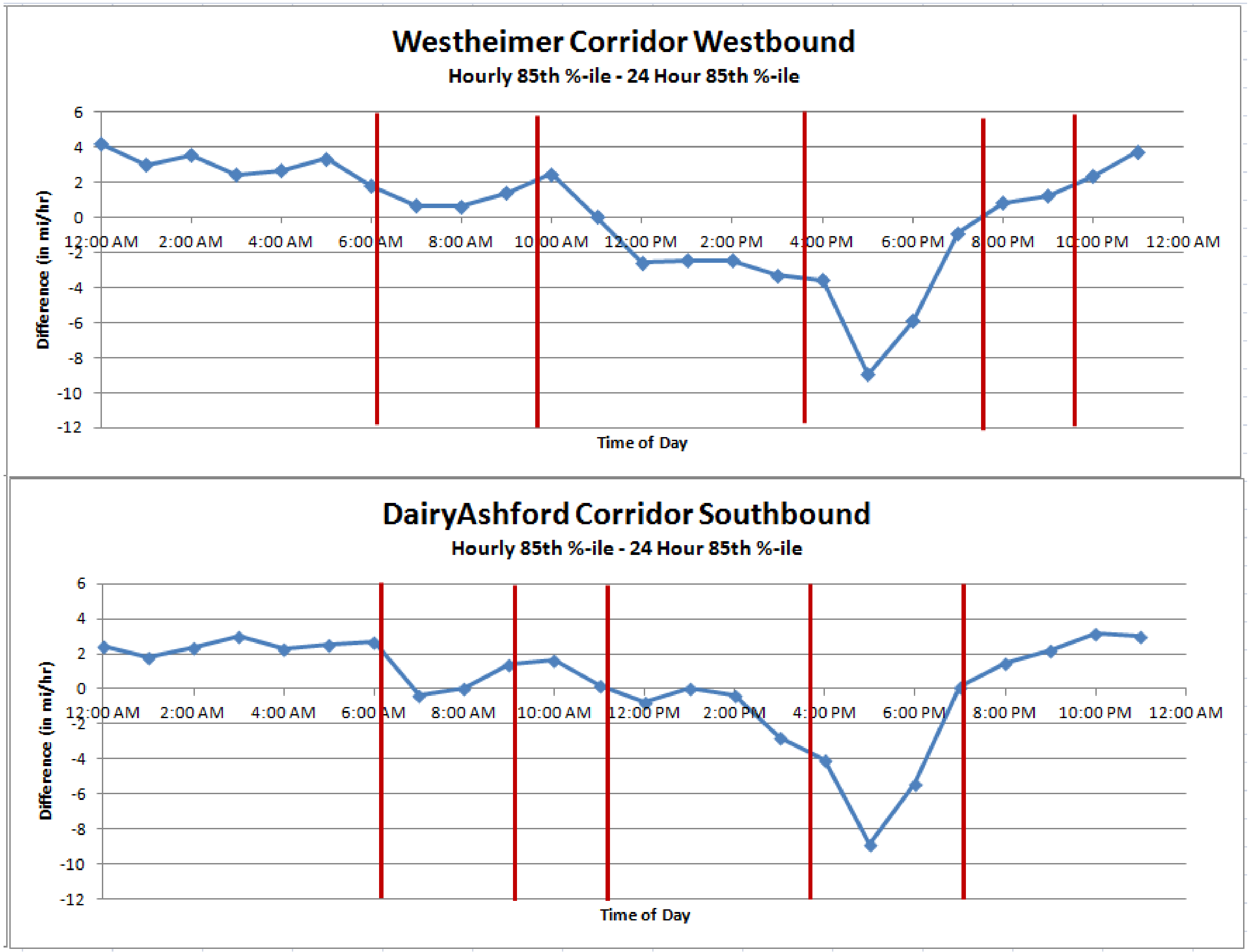

FIGURE 11 Method 2 corridor plots (WB and SB).

The PM peak timing plan begins at 3:30PM for both corridors studied. It is more difficult to predict the PM timing plan changes compared to the AM one. In the PM, the hourly 85th percentile remains lower than the 24-hour 85th percentile until around 6:00PM-8:00PM, depending on the road section. There was a noticeable drop in the hourly 85th percentile during the PM peak for most of the corridor sections examined. The beginning of this decrease might be useful in estimating the beginning of the PM signal timing plan if that information is desired.

The Westheimer corridor reverts back to the off-peak timing plan at 7:30PM and the Dairy Ashford corridor reverts back to the off-peak timing plan at 7:00PM. These times are fairly similar to when the 85th percentiles begin to improve. Therefore, using a daytime 85th percentile from 6:00AM or 7:00AM to 7:00PM or 8:00PM might be useful. For a broader application, one possible way of determining the ending 85th percentile range might be when the hourly 85th percentile equals the 24-hour 85th percentile. For most of the segments this was around 7:00PM-8:00PM, which coincides closely to the end of the PM peak timing plan. A summary of these two methods' proposed criteria for determining daytime peak periods can be found in Table 3.

TABLE 3 Daytime 85th Percentile Criteria

Method	Daytime Period Begins (AM)	Daytime Period ends (PM)
$\frac{Standard\ Deviation\ for\ Each\ Hour}{24\ Hour\ 85th\ Percentile} \leq X$ (Method 1)	When $\frac{Standard\ Deviation\ for\ Each\ Hour}{24\ Hour\ 85th\ Percentile} = 0.13$	Lowest hour between 4PM-8PM
Hourly 85th Percentile – 24 Hour 85th Percentile (Method 2)	First negative Hourly 85th Percentile – 24 Hour 85th Percentile in the AM peak period	Last negative Hourly 85th Percentile – 24 Hour 85th Percentile in the PM peak period

Figure 12 illustrates these new daytime and nighttime 85th percentiles using the two methods previously described. The orange line represents the 24-hour 85th percentile speed that is currently used to determine congestion. The lower red line represents the new daytime 85th percentile speed based on Method 1, while the lower purple line represents the new daytime 85th percentile speed based on Method 2.

FIGURE 12 New 85th percentiles.

From these plots it can be seen that Method 1, in red, tended to end before average speeds return to ‘normal.’ Method 2 tended to have a shorter daytime period, especially for directions experiencing heavy PM directional volumes as seen in Westheimer westbound. However, this was not seen for the Dairy Ashford southbound corridor. After discussion, it was determined that of the two methods, Method 1 seemed to fit the best. After studying timing plans and speed data, it was concluded that the daytime period fits approximately to 6:00AM-7:00PM. This definite timeframe reflects the results of both methods and is easier to process on a large scale than timeframes that can change depending on each segment. Therefore, it was determined that this 6:00AM-7:00PM timeframe for the daytime 85th percentile should be used with the INRIX speed data for determining the daytime reference speed.

After analysis over all five arterial corridors in the study area using the INRIX average speed data, it was found that the 6:00AM-7:00PM 85th percentile produced artificially high speed values that were not representative of actual conditions. This is evident in Figure 13. Based on the findings of this analysis, researchers rejected the notion of using the 85th percentile of the 6:00AM-7:00PM time period as the new reference speed.

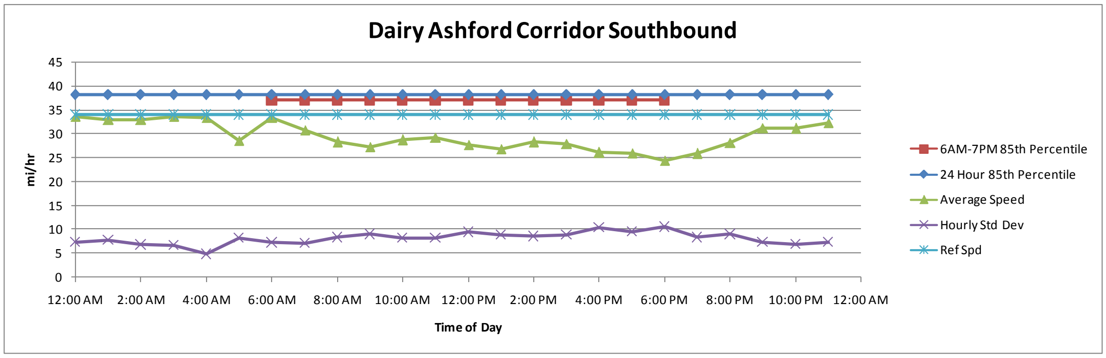

FIGURE 13 Daytime 85th percentile for the Dairy Ashford corridor southbound.

A new methodology had to be developed after the rejection of these two 85th percentile methods. HCM 2010 presents a new methodology using base free-flow speed for determining LOS on arterial streets found in Figure 14. Typically, arterial streets are considered satisfactory if they are operating at LOS C. HCM 2010 defines LOS C as "…stable operation. The ability to maneuver and change lanes at mid-segment locations may be more restricted than at LOS B. Longer queues at the boundary intersection may contribute to lower travel speeds. The travel speed is between 50% and 67% of the base free-flow speed, and the volume-to-capacity ratio is no greater than 1.0" (*4, p. 16-7*).

Travel Speed as a Percentage of Base Free-Flow Speed (%)	LOS by Volume-to-Capacity Ratio[a] ≤1.0	> 1.0
>85	A	F
>67–85	B	F
>50–67	C	F
>40–50	D	F
>30–40	E	F
≤30	F	F

Note: [a]Volume-to-capacity ratio of through movement at downstream boundary intersection.

FIGURE 14 HCM 2010 LOS criteria for automobiles on urban streets (*4*).

Based on this new methodology presented in HCM 2010, researchers explored using other percentiles to accurately represent the reference speed, focusing on the 60th percentile to accurately represent the range of travel speeds described for LOS C. The HCM analyses are typical at the corridor level; the motivation here is to look at the 60th percentile as a possible area-wide analysis. The 60th percentile may not be applicable for a specific corridor. While it does seem reasonable for an aggregate analysis like the UMR, the authors plan to investigate further. Figure 15 represents a range of percentiles (40th, 50th, 60th, 70th, 85th) using INRIX speed data for three of the corridors in the study area. These percentiles are based on average hourly INRIX speed data for the 6AM-7PM period, as determined previously. After analyzing the different percentiles over a variety of corridors it was found that the 60th percentile (seen in green in Figure 15) speeds seem to depict a reasonable reference speed.

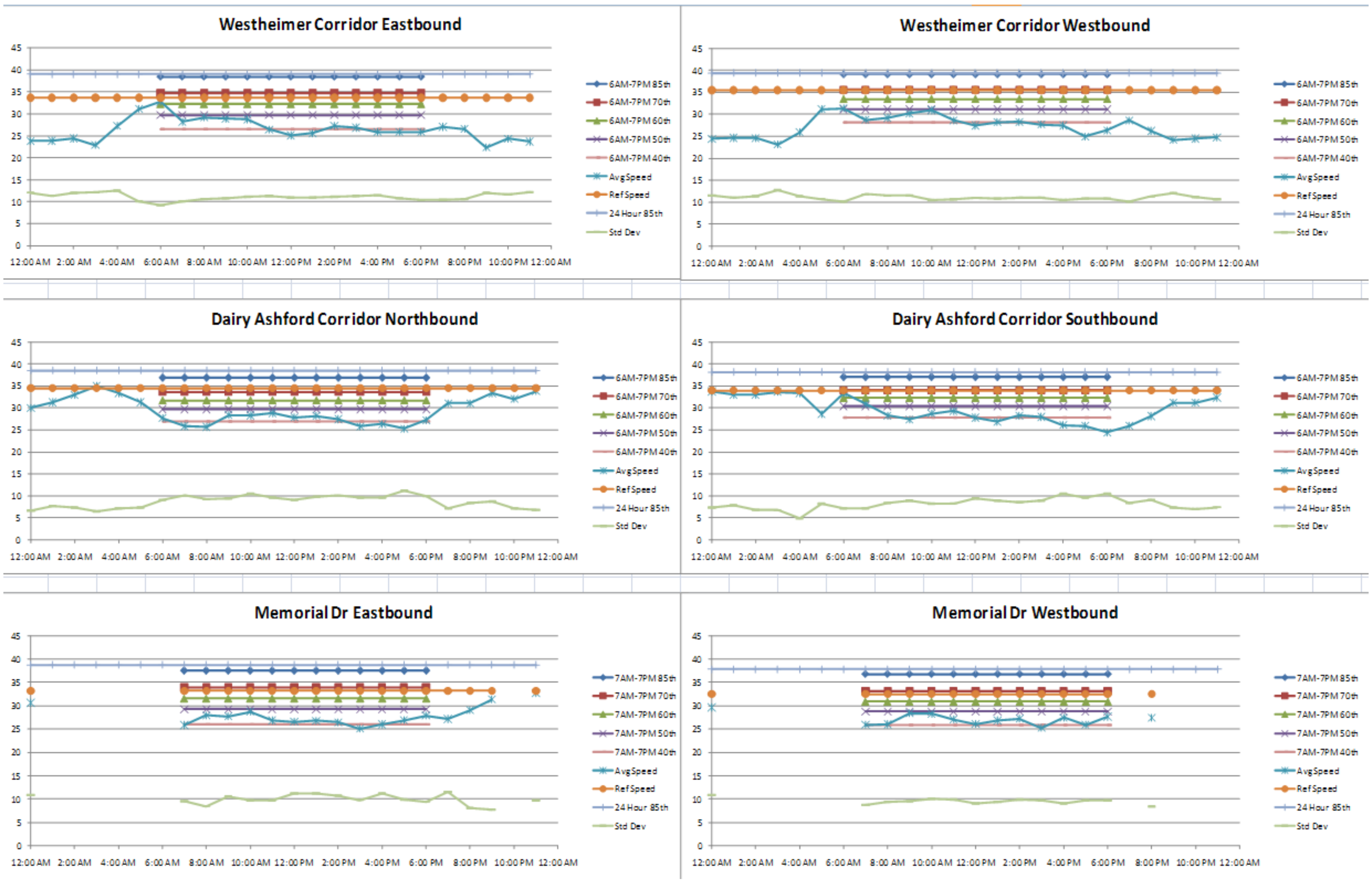

FIGURE 15 INRIX percentiles.

Due to the way interrupted-flow arterials operate, a true base free-flow speed will not be achieved during daytime periods. After studying the data, it was found that this new reference speed accurately depicts what acceptable daytime speeds could be given the proper conditions. As a reference speed, it is used as a benchmark for congestion. As was the case in this study, actual speeds should not exceed it given the heavy daytime traffic volumes. By reducing the reference speed from one that is based on the 85^{th} percentile to the 60^{th} percentile, researchers were able to account for much of the inherent delay on arterials due to the interrupted flow that is not present on freeway systems. This inherent delay produced artificially high congestion numbers for many arterial streets. Addressing this inherent delay allows for a better comparison and understanding of congestion when comparing arterials to freeways, and provides improvements in accuracy and reliability for data found in the UMR congestion report.

As the chosen study area was in a very specific geographic area, additional arterials located in multiple Texas cities were selected for verification. These arterials represented a variety of physical and geometric characteristics. The findings on these arterials coincided with those of the study area. Based on these results, researchers recommend the implementation of the 60^{th} average speed percentile for 6:00AM to 7:00PM to replace the current INRIX reference speed for congestion calculations of arterial streets in the *Urban Mobility Report*.

4.2 DISCUSSION

Interrupted flow found on arterial streets poses new challenges for accurately calculating congestion. New technologies such as GPS provide sufficient data but need refinement. This study validated the use of Bluetooth readers for collecting accurate travel time data, and this thesis discusses current issues with using INRIX speed data and reference speeds on arterial roads.

Multiple methods were explored for determining representative daytime periods and reference speeds. Based on this research, it was found that the 60^{th} percentile for a daytime period of 6:00AM to 7:00PM should be used as the new reference speed when estimating delay. This 60^{th} percentile also reinforces the industry-accepted HCM 2010 methodology while remaining simple to implement. By reducing the reference speed from one that is based on the 85^{th} percentile to the 60^{th} percentile, researchers were able to account for much of the inherent delay that is constantly present on arterials due to the characteristics of interrupted flow that is not present on freeway systems. This allows for a better comparison and understanding of delay when comparing arterials to freeways and provides improvements in accuracy and reliability of data as compared to data found in the UMR congestion report.

5. ANALYSIS OF INTERSECTION/ARTERIAL LOS AND SIGNAL PROGRESSION ALONG A CORRIDOR USING BLUETOOTH DATA

The HCM 2000 method of determining signalized intersection LOS is based on controlled delay, while arterial LOS is based on average travel speed. The objective of this analysis is to compare average intersection LOS and arterial LOS along an arterial corridor and evaluate the effectiveness of signal progression using Bluetooth data in the AM, Midday, and PM peak periods. Average intersection LOS may not be representative of arterial LOS based on HCM methods. This analysis serves to demonstrate a practical application of Bluetooth technology as well as justify the new HCM 2010 arterial LOS methodology compared to the HCM 2000 methodology.

The study area consisted of Westheimer Rd (FM-1093) between TX-6 and Wilcrest Drive in Houston, Texas. An overview of the study area can be found in Figure 16, with the signalized intersections denoted by the triangles.

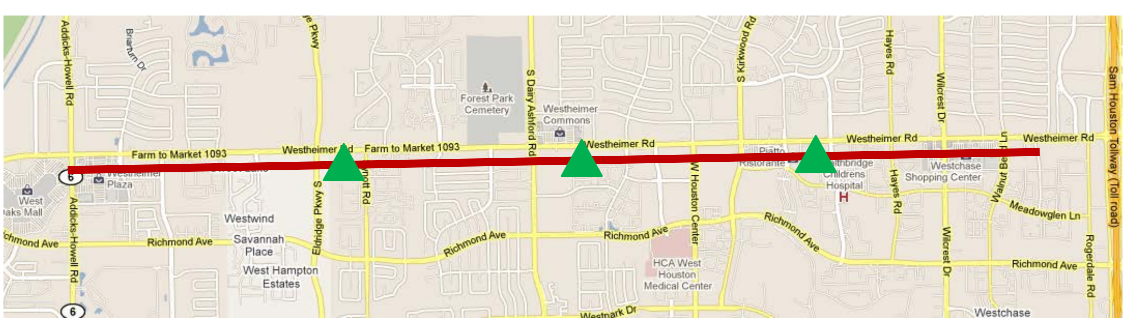

FIGURE 16 Study area.

Bluetooth data for each link on the corridor were analyzed. Data collection start dates varied by link, with the earliest collection beginning on 10/30/2009 for the Kirkwood-Wilcrest segment, and the most recent collection beginning on 4/26/2010 for the Eldridge-Dairy Ashford link. All data used in this analysis had an end date of 1/7/2011. Therefore these data captured a minimum of 9 months worth of data, which was considered a representative sample for this analysis. Using engineering judgment, any travel times that were greater than 15 minutes for a segment were discarded from the analysis, as these readings most likely represented artificial delay caused by motorists making stops along the route and then continuing downstream.

The data were analyzed in 15-minute intervals for the Westheimer corridor from TX-6 to Wilcrest in both directions, as well as between every other signalized intersection to create segments that captured each signalized intersection individually. Using these segments, the HCM 2000 method was applied to determine the level of service for the signalized intersections and the corridor. Corridor travel times and speeds were determined by taking the weighted average of the travel times and speeds of the continuous segments. Each segment was weighted by its distance.

HCM 2000 was used to define the controlled delay per vehicle for the different levels of service for signalized intersections. These thresholds can be found in Table 4. The control delay per vehicle for each intersection was calculated by determining the difference between the average travel times for each 15-minute period and the 85th percentile of the travel times.

TABLE 4 Motor Vehicle LOS Thresholds at Signalized Intersections (*3*)

LOS	Control Delay per Vehicle (seconds)
A	≤ 10
B	> 10-20
C	> 20-35
D	> 35-55
E	> 55-80
F	> 80

Table 5 lists the functional categories for different arterial types as defined by HCM 2000.

TABLE 5 HCM Arterial Class Definitions (*3*)

	Functional Category	
Design Category	**Principal Arterial**	**Minor Arterial**
High-Speed	I	N/A
Suburban	II	II
Immediate	II	III or IV
Urban	III or IV	IV

The Westheimer corridor is considered a principal suburban arterial, and therefore was considered a class II category arterial. Once the urban street class was determined, Table 3-6 from HCM 2000 was used to define the average travel speed ranges for the different LOS classifications. Table 3-6 can be found as Table 6.

TABLE 6 Arterial Level of Service (*3*)

Urban Street Class	**I**	**II**	**III**	**IV**
Range of free-flow speed (FFS)	55 to 45 mph	45 to 35 mph	35 to 30 mph	35 to 25 mph
Typical FFS	50 mph	40 mph	35 mph	30 mph
LOS	**Average Travel Speed (mph)**			
A	> 42	> 35	> 30	> 25
B	> 34-42	> 28-35	> 24-30	> 19-25
C	> 27-34	> 22-28	> 18-24	> 13-19
D	> 21-27	> 17-22	> 14-18	> 9-13
E	> 16-21	> 13-17	> 10-14	> 7-9
F	≤ 16	≤ 10	≤ 10	≤ 7

Signal timing plans were consulted to determine the AM and PM peak periods. Different signal timing plans are used for different periods of the day. These timing plans change throughout the day in order to meet current traffic patterns. The peak periods used in this study were: an AM peak period of 6AM-9:30AM, a Midday peak period of 11AM-2PM, and a PM peak period of 3:30PM-7:30PM. In order to determine an average LOS for each peak period and direction, a numerical value was assigned to each level of service, as seen in Table 7.

TABLE 7 Level of Service Values

LOS	Numerical Value
A	1
B	2
C	3
D	4
E	5
F	6

The LOS was calculated for the corridor and for each intersection for each 15-minute interval, and converted into a numerical value. All three intersection LOSs were averaged for each 15-minute interval, and the 15-minute intervals for each peak period were averaged to determine a numerical LOS average for each peak period.

5.1 Data/Results

Using the methods stated in the above section, the intersection and arterial LOSs were calculated as shown in Table 8. The AM peak is similar in both directions and the PM peak is worse in the WB direction.

TABLE 8 LOS Results

		EB			WB			Corridor	
		Signalized Intersection			Signalized Intersection			EB	WB
From	To	Eldridge	Dairy Ashford	Kirkwood	Kirkwood	Dairy Ashford	Eldridge		
6:00	6:15	A	B	A	E	E	B	B	B
6:15	6:30	A	B	A	D	D	A	B	B
6:30	6:45	A	A	A	D	D	A	B	B
6:45	7:00	B	A	B	E	E	A	B	B
7:00	7:15	C	B	C	D	D	A	B	B
7:15	7:30	E	D	E	E	D	E	C	C
7:30	7:45	F	F	F	D	D	D	C	B
7:45	8:00	F	F	F	E	D	C	C	B
8:00	8:15	E	F	F	D	D	E	C	C
8:15	8:30	D	E	D	B	E	D	C	B
8:30	8:45	C	C	C	C	A	C	B	B
8:45	9:00	B	A	B	D	B	C	B	B
9:00	9:15	A	A	B	E	C	B	B	B
9:15	9:30	B	B	C	E	B	E	B	C
11:00	11:15	D	C	D	C	D	A	B	B
11:15	11:30	B	C	D	C	C	B	B	B
11:30	11:45	C	E	C	E	F	D	B	C
11:45	12:00	C	F	E	E	D	A	C	B
12:00	12:15	C	E	F	F	D	C	C	C
12:15	12:30	D	F	F	F	C	D	C	C
12:30	12:45	C	D	D	E	D	C	B	B
12:45	13:00	C	C	E	D	D	C	B	B
13:00	13:15	C	D	D	D	C	C	B	B
13:15	13:30	C	C	E	E	D	B	B	B
13:30	13:45	D	D	E	D	D	C	C	B
13:45	14:00	D	D	D	D	D	C	C	B
15:30	15:45	C	E	F	F	E	C	C	C
15:45	16:00	D	D	E	E	E	D	C	C
16:00	16:15	C	D	E	E	D	C	C	C
16:15	16:30	B	E	F	D	E	D	C	C
16:30	16:45	D	D	D	E	F	E	B	C
16:45	17:00	C	E	E	F	F	F	C	D
17:00	17:15	D	E	F	F	F	F	C	D
17:15	17:30	B	D	F	F	F	F	C	D
17:30	17:45	A	D	E	F	F	F	B	E
17:45	18:00	D	D	D	F	F	F	B	D
18:00	18:15	C	D	E	F	F	F	B	D
18:15	18:30	C	D	E	F	F	F	C	D
18:30	18:45	C	D	D	F	F	F	B	D
18:45	19:00	C	D	D	F	F	F	B	D
19:00	19:15	C	D	E	F	F	F	C	C
19:15	19:30	B	C	D	F	F	E	B	C

The intersection LOS was then compared to the arterial LOS, which was determined following HCM 2000 methods and the calculated average travel speed. From Table 8, it can be seen that during the same AM and PM peak periods, the arterial LOS decreased, but not as substantially as the intersection LOS. Unlike the intersection LOS, the arterial LOS never fell to a level of F.

Using Table 7, the LOSs were converted into numerical values in order to determine an aggregate average LOS for all the intersections along the corridor. Using this numerical method, the average LOS values shown in Table 9 were calculated.

TABLE 9 Peak-Period Average LOS

	EB		WB	
	Intersection LOS	**Corridor LOS**	**Intersection LOS**	**Corridor LOS**
AM Average	C (3.07)	B (2.36)	D (3.57)	B (2.21)
Midday Average	D (4)	B (2.42)	D (3.69)	B (2.25)
PM Average	D (4.02)	C (2.56)	F (5.54)	D (3.63)

The numerical averages of the LOS for each peak period illustrate the differences between intersection LOS and corridor LOS. For every peak period in both directions the intersection LOS was worse than the comparable corridor LOS. One possible explanation for this disparity in LOS is that the majority of the delay and resulting decreased average travel speed are being caused at signalized intersections. This particular corridor has a sufficient signalized intersection spacing of about 1 mile, which is enough distance for vehicles to accelerate back to their desired speeds, conditions permitting. This increased speed between intersections dilutes the controlled delay the signalized intersections are causing. It is important to note that the intersection LOS found in Table 6 for the AM peak is worse in the WB direction. This signifies that signal progression is performing as intended during the AM peak period by giving favorable treatment to the EB direction as it experiences higher volumes. Offsets between the two directions are not independent. Changing the offset to benefit one direction will impact the opposing through direction’s offsets.

In order to better compare the AM peak and PM peak, the 15-minute average travel time and average travel speed for the corridor were graphed for each direction and can be seen in Figures 17 and 18.

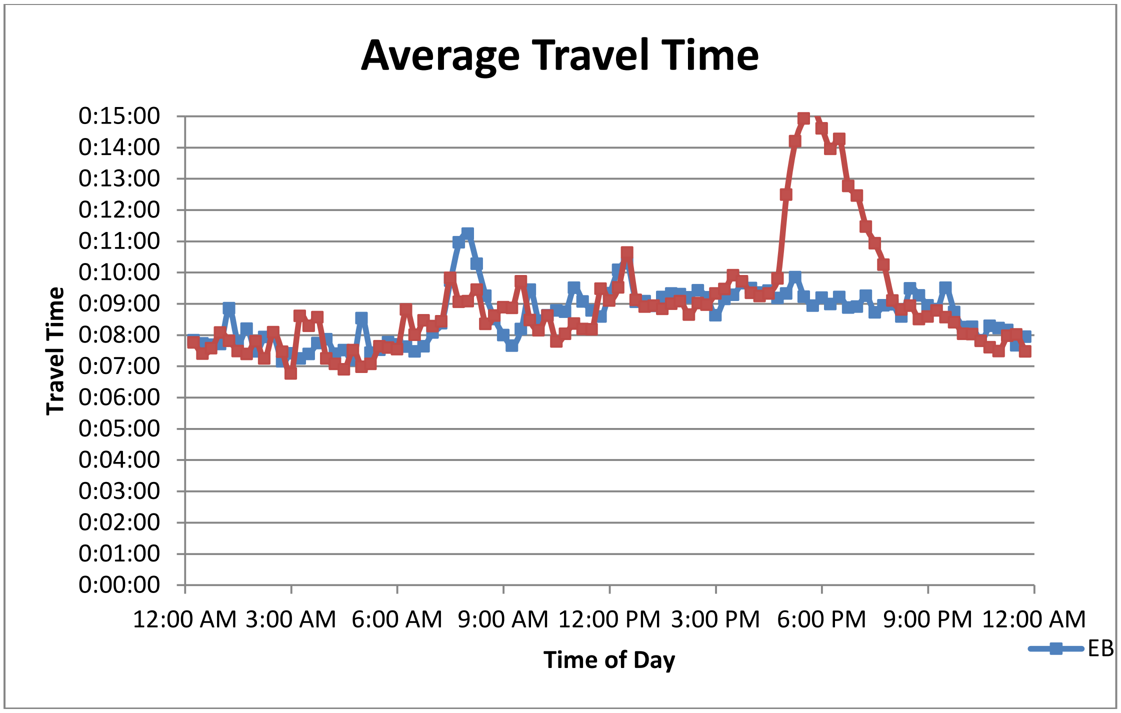

FIGURE 17 Average travel time.

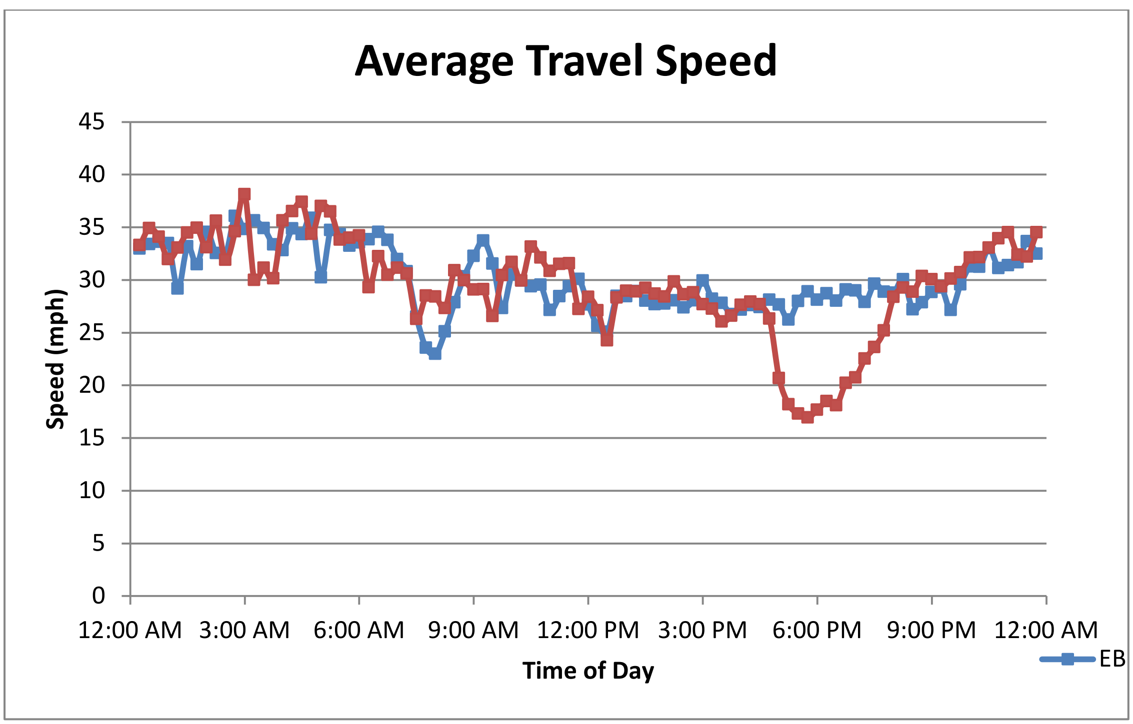

FIGURE 18 Average travel speed.

In these two figures, the increased travel time and decreased travel speed can be seen in the AM for the EB direction and in the PM for the WB direction. The conditions continually degrade throughout the day in both directions. It is apparent that the PM period in the WB direction suffers from substantially lower speeds and higher travel times (almost 4 minutes higher) than the AM period in the EB direction. One possible cause of this difference could be the higher volumes in the PM peak than in the AM peak. In order to investigate this, 15-minute vehicle counts were used to construct a volume graph for each direction, which can be seen in Figure 19.

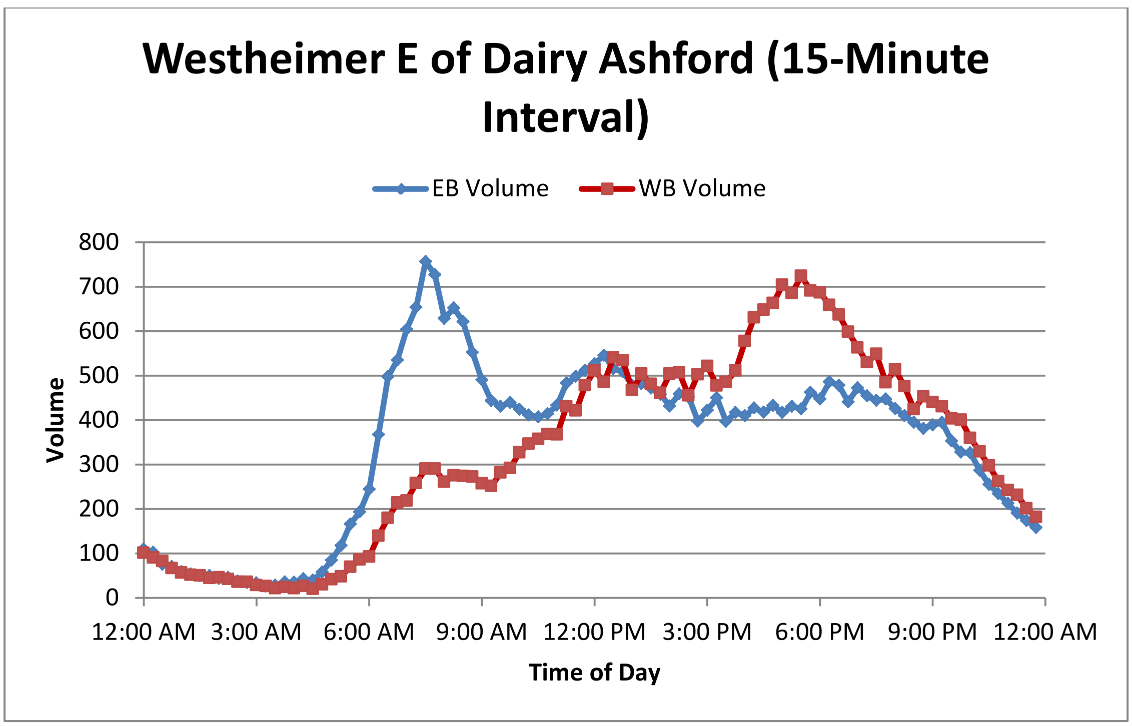

FIGURE 19 15-minute volume counts.

In this figure, it can be seen that the AM peak in the EB direction and the PM peak in the WB direction experienced very similar 15-minute volume counts for similar periods of time, and should therefore have similar LOSs. The AM peak experiences a sharp increase in volume whereas the PM peak gradually increases throughout the day.

This analysis indicates that both directions experience very similar volume counts, yet the WB PM peak has considerably worse intersection LOSs and overall arterial LOSs (and the associated increased travel times) than the EB AM peak. The WB PM peak experiences these significantly degraded conditions for a longer period than the EB AM peak.

From these results, several causes of the differing AM and PM peak travel times appear likely: one being different approaches to the signal progression in the AM compared to the PM. Although both peak periods experience similar volumes in the dominant direction, the PM peak experiences a flow almost twice as high as the AM peak in the opposing direction. Engineers are afforded the ability to provide a timing plan that emphasizes a more one-way progression in the morning, which they cannot effectively apply in the evening. This is most likely one of the main causes for the increased travel time in the PM peak. When running properly, signal coordination is used to give priority to the direction with the higher volume, and should result in similar travel times in each direction even though the volume is substantially higher in one direction.

A second possible cause is that in the AM peak many motorists are commuting to work and do not make any stops. In the afternoon however, many motorists will stop on their trip home to run errands, and these additional trips will cause an increase in vehicles entering and exiting the travel way, at intersections or in mid-block, causing decreased speeds and increased travel times for all motorists impacted by these increased movements. The controlled delay experienced at each intersection for the peak periods can be seen in Table 10.

TABLE 10 Intersection Controlled Delay

Intersection	Direction	Avg Control Delay (s)	6AM-9:30AM Control Delay (s)	11AM-2PM Control Delay (s)	3:30PM-7:30PM Control Delay (s)
Eldridge	EB	22.19	17.11	32.73	27.82
Dairy Ashford	EB	30.15	17.13	52.2	48.93
Kirkwood	EB	38.26	20.7	63.43	67.24
Eldridge	WB	33.46	17.14	23.79	122.6
Dairy Ashford	WB	51.37	22.4	41.21	175.49
Kirkwood	WB	48.47	24.18	61.02	136.31

It was found that the AM and Midday peak periods experienced similar control delays in both directions, while the WB direction had significantly higher control delay at all three intersections in the PM peak period. This illustrates that signal progression is working efficiently in the AM peak and that further investigation of the signal timing plans should be conducted for the PM movements.

5.2 COMPARISON OF HCM 2000 AND HCM 2010 ARTERIAL LOS RESULTS

In order to calculate arterial LOS using HCM methodologies, a base free-flow speed of 40 mph was determined using the arterial classification methodology described in HCM 2000 for the study corridor, and verified as the posted speed limit. This value was used in the calculation of LOS for the HCM 2010 methodology, as described in Figure 14. The corridor LOS results using these two methodologies can be found in Table 11.

Slight differences in the LOS between the two HCM methodologies were found. These differences might be explained by the fact that the HCM 2000 methodology uses a method that groups roadways into general classifications using a general FFS, while the new HCM 2010 methodology uses a base FFS specific to each roadway. The former method uses a grouping of average travel speeds to determine the LOS, while the latter uses a grouping of travel speeds as a percentage of the base free-flow speed. The new HCM 2010 methodology seems more capable of being tailored to individual roadways.

TABLE 11 Arterial LOS Using Different HCM Methodologies

Westheimer Corridor					
From	**To**	**HCM 2000 EB**	**HCM 2010 EB**	**HCM 2000 WB**	**HCM 2010 WB**
6:00	6:15	B	B	B	B
6:15	6:30	B	A	B	B
6:30	6:45	B	B	B	B
6:45	7:00	B	B	B	B
7:00	7:15	B	B	B	B
7:15	7:30	C	C	C	C
7:30	7:45	C	C	B	B
7:45	8:00	C	C	B	B
8:00	8:15	C	C	C	B
8:15	8:30	C	B	B	B
8:30	8:45	B	B	B	B
8:45	9:00	B	B	B	B
9:00	9:15	B	B	B	B
9:15	9:30	B	B	C	C
11:00	11:15	B	B	B	B
11:15	11:30	B	B	B	B
11:30	11:45	B	B	C	B
11:45	12:00	C	B	B	B
12:00	12:15	C	C	C	B
12:15	12:30	C	C	C	C
12:30	12:45	B	B	B	B
12:45	13:00	B	B	B	B
13:00	13:15	B	B	B	B
13:15	13:30	B	B	B	B
13:30	13:45	C	B	B	B
13:45	14:00	C	B	B	B
15:30	15:45	C	C	C	C
15:45	16:00	C	B	C	B
16:00	16:15	C	B	C	B
16:15	16:30	C	B	C	B
16:30	16:45	B	B	C	C
16:45	17:00	C	B	D	C
17:00	17:15	C	C	D	D
17:15	17:30	C	B	D	D
17:30	17:45	B	B	E	D
17:45	18:00	B	B	D	D
18:00	18:15	B	B	D	D
18:15	18:30	C	B	D	D
18:30	18:45	B	B	D	C
18:45	19:00	B	B	D	C
19:00	19:15	C	B	C	C
19:15	19:30	B	B	C	C

While both methodologies produced the same results for most of the time intervals, occasional discrepancies were still found, with the 2010 methodology yielding a higher LOS in every instance. With these two methodologies in widespread use, it is important for practitioners to note which method was used. If the method is not identified and noted, the public might see these changes as an improvement in the road system rather than as a change in evaluation.

5.3 COMPARISON OF HCM AND BLUETOOTH SEGMENT AND CORRIDOR TRAVEL TIMES

Further investigation of arterial LOS and intersection LOS was performed by comparing Bluetooth data to the HCM 2000 procedure for calculating segment and corridor speeds. In order to compute the travel speed, the through delay and the travel time had to be determined. The through delay is the sum of the controlled delay, or the delay due to the traffic control at the boundary intersection, and geometric delay. The geometric delay is considered to be negligible in conventional four-leg intersections (*4*). The control delay was computed by taking the difference between segments that included the intersection and the sum of the two segments on either side of that intersection. For instance, there is segment A-B and B-C, where point B is the intersection. The difference in travel time between segment A-C and the sum of A-B and B-C is the controlled delay.

The computed control delay for the intersections can be seen in Table 12. While the results appear somewhat sporadic, there is noticeably more delay during the PM peak period in both directions than at any other time.

TABLE 12 Control Delay

Signalized Intersection							
From	**To**	**Eldridge (EB) (s)**	**Dairy Ashford (EB) (s)**	**Kirkwood (EB) (s)**	**Kirkwood (WB) (s)**	**Dairy Ashford (WB) (s)**	**Eldridge (WB) (s)**
6:00	6:15		0:00:33				
6:15	6:30						
6:30	6:45						
6:45	7:00				0:00:09		
7:00	7:15	0:00:02		0:00:47		0:00:08	
7:15	7:30				0:00:03	0:00:03	
7:30	7:45			0:00:03		0:00:03	0:00:01
7:45	8:00						0:00:17
8:00	8:15	0:00:02	0:01:46				
8:15	8:30		0:00:29		0:00:02		
8:30	8:45	0:00:01			0:00:07		0:00:09
8:45	9:00	0:00:04					
9:00	9:15			0:00:02	0:00:09		0:00:55
9:15	9:30				0:00:35		
11:00	11:15				0:00:42		
11:15	11:30	0:00:12			0:00:09	0:00:01	
11:30	11:45	0:00:03					
11:45	12:00			0:00:13			
12:00	12:15					0:00:04	
12:15	12:30	0:00:34					
12:30	12:45					0:00:02	0:00:10
12:45	13:00						0:00:20
13:00	13:15	0:00:20					0:00:02
13:15	13:30	0:00:03					0:00:02
13:30	13:45	0:00:09	0:00:10		0:00:21	0:00:37	
13:45	14:00	0:00:07	0:00:17		0:00:07	0:00:28	

TABLE 12 Continued

From	To	Eldridge (EB) (s)	Dairy Ashford (EB) (s)	Kirkwood (EB) (s)	Kirkwood (WB) (s)	Dairy Ashford (WB) (s)	Eldridge (WB) (s)
15:30	15:45	0:00:06			0:00:07	0:00:22	
15:45	16:00	0:00:07				0:00:28	
16:00	16:15	0:00:05	0:00:02	0:00:08		0:00:14	
16:15	16:30	0:00:07	0:00:01	0:00:14	0:00:13	0:00:12	0:00:08
16:30	16:45	0:00:09	0:00:17	0:00:08			
16:45	17:00		0:00:02			0:00:04	
17:00	17:15		0:00:03	0:00:06		0:00:17	
17:15	17:30			0:00:01		0:00:38	
17:30	17:45			0:00:01			
17:45	18:00						
18:00	18:15				0:00:18		
18:15	18:30	0:00:02			0:00:03		
18:30	18:45	0:00:01			0:00:01		
18:45	19:00					0:00:06	0:00:02
19:00	19:15				0:00:14	0:00:07	0:00:06
19:15	19:30						

Using the calculated control delay as the HCM control delay, segment travel time can be determined by summing segment running time and the control delay. Segment running time was determined from Exhibit 15-3 in HCM 2000. Segment travel time is shown in Table 13, and corridor travel times can be seen in Figures 20 and 21.

TABLE 13 Segment Travel Time

From	To	SH6-Dairy Ashford (EB) (s)	Eldridge-Kirkwood (EB) (s)	Dairy Ashford-Wilcrest (EB) (s)	Wilcrest-Dairy Ashford (WB) (s)	Kirkwood-Eldridge (WB) (s)	Eldridge-SH6 (WB) (s)
6:00	6:15	0:02:43	0:03:16	0:02:43	0:02:43	0:02:43	0:02:43
6:15	6:30	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43
6:30	6:45	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43
6:45	7:00	0:02:43	0:02:43	0:02:43	0:02:52	0:02:43	0:02:43
7:00	7:15	0:02:45	0:02:43	0:03:30	0:02:43	0:02:51	0:02:43
7:15	7:30	0:02:43	0:02:43	0:02:43	0:02:46	0:02:46	0:02:43
7:30	7:45	0:02:43	0:02:43	0:02:46	0:02:43	0:02:46	0:02:44
7:45	8:00	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43	0:03:00
8:00	8:15	0:02:45	0:04:29	0:02:43	0:02:43	0:02:43	0:02:43
8:15	8:30	0:02:43	0:03:12	0:02:43	0:02:45	0:02:43	0:02:43
8:30	8:45	0:02:44	0:02:43	0:02:43	0:02:50	0:02:43	0:02:52
8:45	9:00	0:02:47	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43
9:00	9:15	0:02:43	0:02:43	0:02:45	0:02:52	0:02:43	0:03:38
9:15	9:30	0:02:43	0:02:43	0:02:43	0:03:18	0:02:43	0:02:43
11:00	11:15	0:02:43	0:02:43	0:02:43	0:03:25	0:02:43	0:02:43
11:15	11:30	0:02:55	0:02:43	0:02:43	0:02:52	0:02:44	0:02:43
11:30	11:45	0:02:46	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43
11:45	12:00	0:02:43	0:02:43	0:02:56	0:02:43	0:02:43	0:02:43
12:00	12:15	0:02:43	0:02:43	0:02:43	0:02:43	0:02:47	0:02:43
12:15	12:30	0:03:17	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43
12:30	12:45	0:02:43	0:02:43	0:02:43	0:02:43	0:02:45	0:02:53
12:45	13:00	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43	0:03:03
13:00	13:15	0:03:03	0:02:43	0:02:43	0:02:43	0:02:43	0:02:45
13:15	13:30	0:02:46	0:02:43	0:02:43	0:02:43	0:02:43	0:02:45
13:30	13:45	0:02:52	0:02:53	0:02:43	0:03:04	0:03:20	0:02:43
13:45	14:00	0:02:50	0:03:00	0:02:43	0:02:50	0:03:11	0:02:43
15:30	15:45	0:02:49	0:02:43	0:02:43	0:02:50	0:03:05	0:02:43
15:45	16:00	0:02:50	0:02:43	0:02:43	0:02:43	0:03:11	0:02:43
16:00	16:15	0:02:48	0:02:45	0:02:51	0:02:43	0:02:57	0:02:43
16:15	16:30	0:02:50	0:02:44	0:02:57	0:02:56	0:02:55	0:02:51
16:30	16:45	0:02:52	0:03:00	0:02:51	0:02:43	0:02:43	0:02:43
16:45	17:00	0:02:43	0:02:45	0:02:43	0:02:43	0:02:47	0:02:43
17:00	17:15	0:02:43	0:02:46	0:02:49	0:02:43	0:03:00	0:02:43
17:15	17:30	0:02:43	0:02:43	0:02:44	0:02:43	0:03:21	0:02:43
17:30	17:45	0:02:43	0:02:43	0:02:44	0:02:43	0:02:43	0:02:43
17:45	18:00	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43
18:00	18:15	0:02:43	0:02:43	0:02:43	0:03:01	0:02:43	0:02:43
18:15	18:30	0:02:45	0:02:43	0:02:43	0:02:46	0:02:43	0:02:43
18:30	18:45	0:02:44	0:02:43	0:02:43	0:02:44	0:02:43	0:02:43
18:45	19:00	0:02:43	0:02:43	0:02:43	0:02:43	0:02:49	0:02:45
19:00	19:15	0:02:43	0:02:43	0:02:43	0:02:57	0:02:50	0:02:49
19:15	19:30	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43	0:02:43

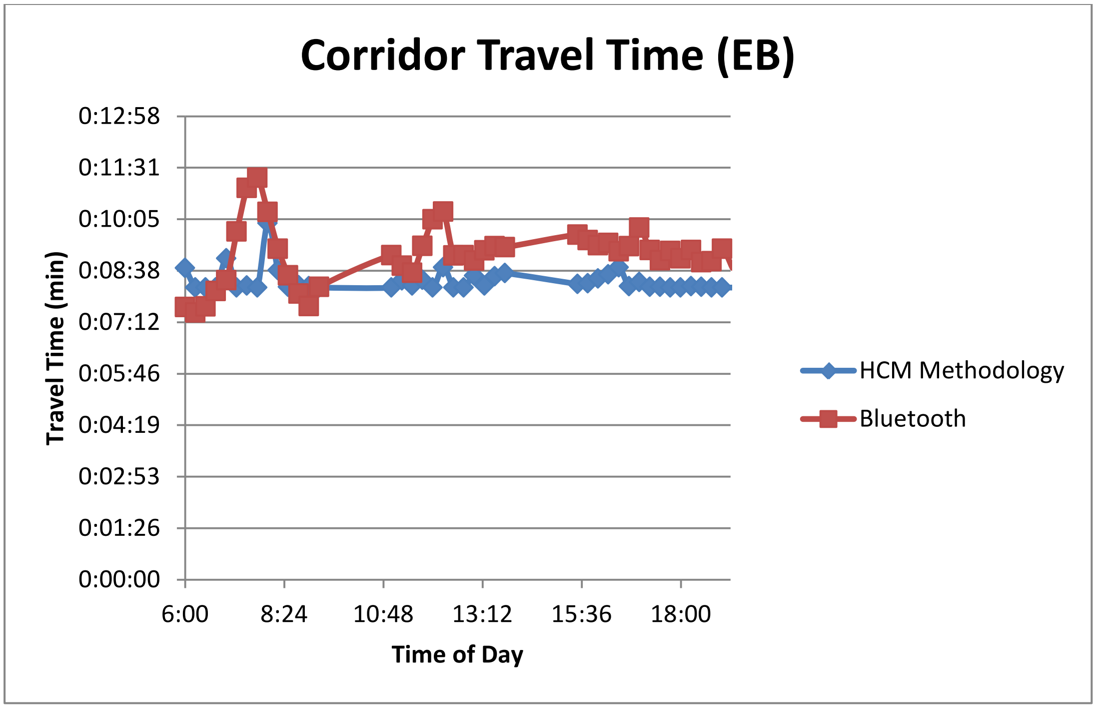

FIGURE 20 Corridor travel time (EB).

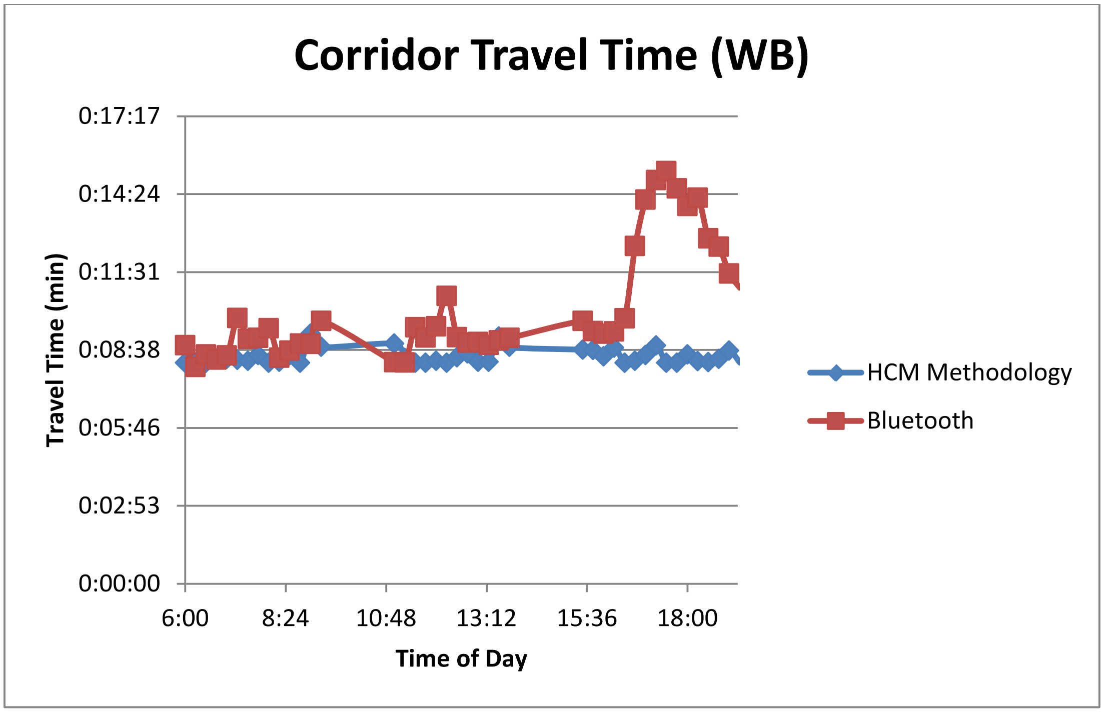

FIGURE 21 Corridor travel time (WB).

5.4 DISCUSSION

The arterial LOS analysis in this study demonstrated that both HCM 2000 and HCM 2010 produced similarly satisfying results. The comparison to Bluetooth data in Figure 21 illustrates the discrepancies between the HCM methods and real-world data. While HCM 2000 requires engineers to use their own judgment to classify roadways, HCM 2010 methodology is a more simplified method that produces accurate results while removing human judgment when classifying roadways. HCM 2010 is a better methodology as it is easier to use, more accurate, and more methodical.

While both of the HCM methodologies for arterial LOS are widely accepted as accurate, they are not without limitations. Neither methodology accounts for variables such as block distance or signal spacing, both of which have a significant impact on arterial LOS. If signals are spaced too closely to each other, traffic progression may be hindered and queue backups can occur at high-volume intersections. It is important to space traffic signals as evenly as possible, and a spacing of approximately ½ mile is recommended for most busy corridors (*1*5). If signals are spaced too far apart, a breakup of the platoons is possible due to access movements, lane changes, and varying travel speeds (*15*). Figure 22 shows the relationship between signal spacing and speed. As signal spacing decreases, speed typically decreases and the LOS should go down. In order to mitigate this impact, a signal spacing reduction factor might need to be implemented to account for varying signal spacing.

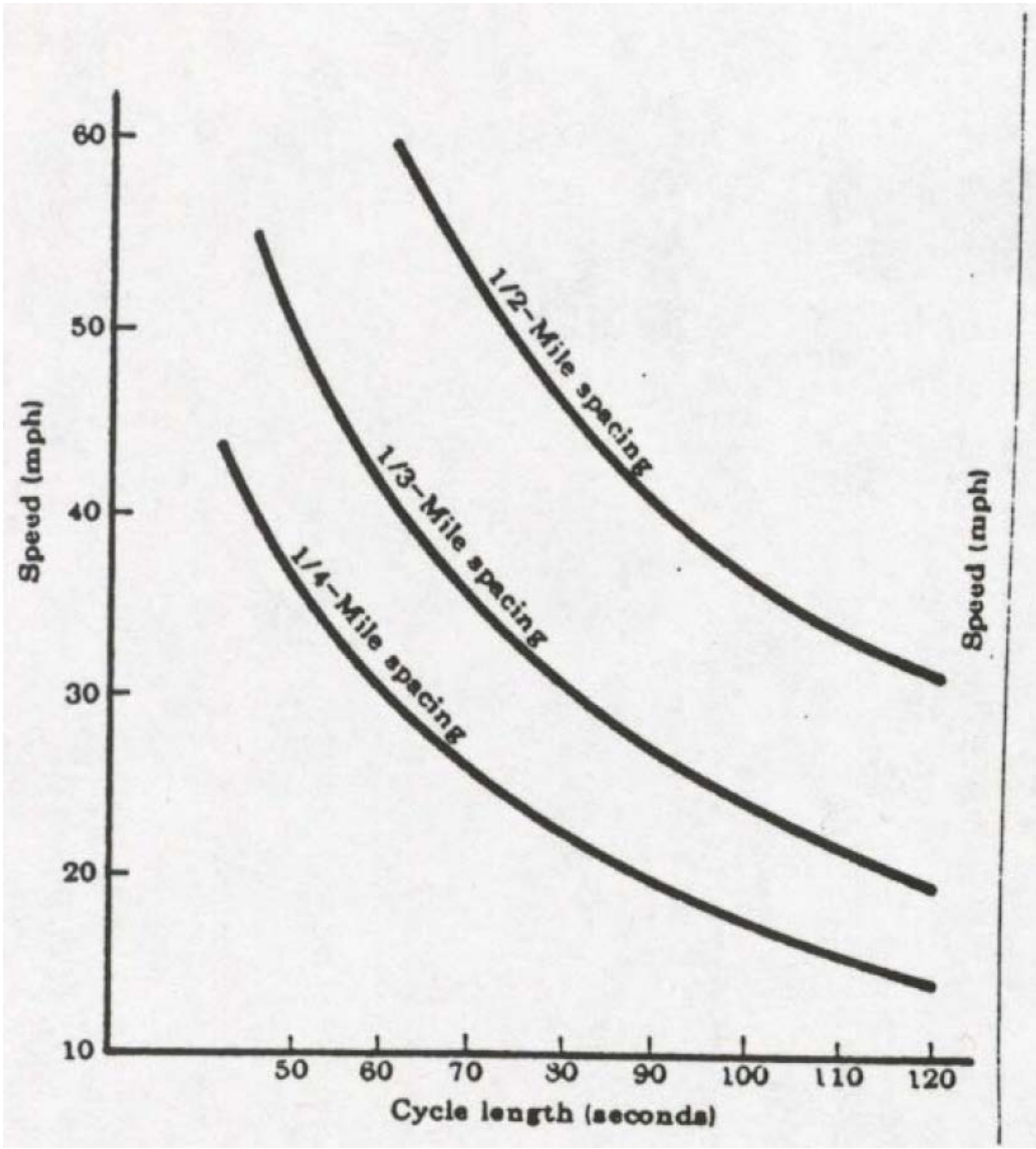

FIGURE 22 Cycle length, speed, and signal spacing (*15*).

For this analysis, signals were evenly spaced at about 1 mile, and further investigation should be performed on arterials with larger signal spacing before developing a relationship between intersection LOS and corridor LOS. Other factors such as time of day and origin-destination of trips can impact the level of service, as seen in the LOS analysis. However, this might not be the only cause for disparities. If there is a disparity in the level of service under similar volumes, this could also be an indicator that the timing plans and the signal coordination should be analyzed for issues and optimized when needed. A timing plan might be optimized for the AM peak period in one direction, but due to different opposing flow conditions, cannot be applied as effectively in the PM peak period.

One would expect similar or better travel times in the peak direction due to proper signal coordination. As was seen in this analysis in the AM peak period, travel time increased only marginally in the EB direction compared to the WB direction. For the PM peak period, however, travel time for the WB direction increased drastically when compared to the EB direction. This difference in travel time is most likely due to the timing plans accounting for the increased volume in the non-peak direction.

The results of the control delay and travel time analyses show that the HCM methodology consistently produces faster travel times than those recorded by Bluetooth readers. This could be due in part because HCM 2000 methodology does not account for signal coordination nor does it account for specific signal spacing. As the signal density increases, the control delay becomes a larger part of the overall travel time, especially when analyzing a longer corridor with many signals. The methodology also requires interpolation and extrapolation to set values not listed in the exhibit, which introduces room for possible error.

For determining segment and corridor travel times, HCM 2010 is preferred over HCM 2000 as it better accounts for variables such as demand flow rate, delay caused by turning movements into access point intersections, and the number of influential access points. HCM 2000 methodology was used in this comparison because demand flow rates were not available for the segments. This study illustrated the ability of Bluetooth readers to better capture the highs and lows of corridor travel time compared to HCM calculations. However, a larger Bluetooth dataset could produce more accurate intersection control delay values, resulting in improved HCM values.

The findings of this investigation show that Bluetooth reader technology is a viable and cost-efficient way of gathering reliable travel time data on arterial streets. This technology can and should be used by government entities to evaluate traffic patterns on heavily congested corridors and update timing schemes accordingly.

6. CONCLUSIONS

Interrupted traffic flow found on arterial streets poses new challenges for accurately calculating congestion. New technologies such as GPS provide sufficient data but need refinement. This study validated the use of Bluetooth readers for collecting accurate travel time data and addressed current issues with using INRIX speed data and reference speeds on arterial roads.

By performing visual inspection of a multitude of percentiles, the 60th percentile for a daytime period of 6:00AM to 7:00PM was found to depict a reasonable reference speed. This 60th percentile also reinforces the HCM 2010 methodology while remaining simple to implement. By reducing the reference speed from one that is based on the 85th percentile to the 60th percentile, a lot of inherent delay that is constantly present on arterials due to interrupted flow not present on freeway systems is removed. This allows for a better comparison and understanding of delay when comparing arterials to freeways and provides improvements in accuracy and reliability of data when compared to data found in the UMR congestion report.

HCM analyses are typical at the corridor level. The motivation in this study was to look at the 60th percentile for an area-wide analysis. The 60th percentile may not be applicable for a specific corridor. While it does seem reasonable for an aggregate analysis like the UMR, the authors plan to investigate further. There are some limitations to this methodology including volume changes and signal spacing. The reference speed needs to be reevaluated under differing conditions, and limitations need further investigation.

The arterial LOS analysis in this study demonstrated that both HCM 2000 and HCM 2010 produced similar results. While HCM 2000 requires engineers to use their own judgment to classify roadways, HCM 2010 is a simplified method that produces accurate results while removing human judgment when classifying roadways. HCM 2010 is a better methodology as it is easier to use, just as accurate as previous methods, and more methodical.

This analysis also concluded that signalized intersection LOS does not accurately reflect arterial corridor LOS. The spacing of signalized intersections (block distance) will greatly influence the impact on arterial LOS. For this analysis, signals were evenly spaced at about 1 mile, and further investigation should be performed on arterials with larger signal spacing before developing a relationship between intersection LOS and corridor LOS.

The findings of this investigation show that Bluetooth reader technology and INRIX probe-sourced data are both viable and cost-efficient ways of gathering reliable travel time data on arterial streets. The large size, frequency, and availability of the Bluetooth and INRIX datasets could enable engineers to develop better LOS measures. These data sources are better than traditional methods because they provide a broader sample of conditions. As Bluetooth and GPS data become more common on vehicles and personal devices, sample rates will increase. Future LOS measures using this high sample rate data might involve measuring the quality of platooning that is occurring on an arterial, allowing engineers to better gauge the effectiveness of signal timing.

REFERENCES

1. Haghani, A., Hamedi, M., Sadabadi, K., Young, S., Tarnoff, P. Data Collection of Freeway Travel Time Ground Truth with Bluetooth Sensors. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 2160. Transportation Research Board of the National Academies, Washington, DC, 2010, pp. 60-68.

2. INRIX National Traffic Scorecard. In *INRIX 2009 Annual Report*, Kirkland, WA, 2009, pp. 4.

3. *Highway Capacity Manual.* Transportation Research Board of the National Academies, Washington, DC, 2000.

4. *Highway Capacity Manual.* Transportation Research Board of the National Academies, Washington, DC, 2010.

5. *Urban Mobility Report.* Texas Transportation Institute, College Station, TX, 2012.

6. Puckett, D., and M. Vickich. *Bluetooth-Based Travel Time/Speed Measuring Systems Development.* University Transportation Center for Mobility, Texas Transportation Institute, College Station, TX, 2010.

7. *FY2010 Task 1.2 Technical Report – Bluetooth-based Travel Time Data Collection.* Texas Transportation Institute, College Station, TX, 2010.

8. Wasson, J., J. Sturdevant, D. Bullock. Real-Time Travel Time Estimates Using Media Access Control Address Matching. *ITE Journal*, Vol. 27, No. 6, June 2008.

9. Traffax, *BlueSTATs Operations Manual*, *BluSTATs version 1.2B*, February 16, 2009.

10. Young, S. *Bluetooth Traffic Monitoring.* Traffax Inc. & University of Maryland Center for Advanced Transportation Technology, Bluetooth Summit, Houston, TX, February 2010.

11. Haghani, A., and M. Hamedia. *Using Bluetooth Technology for Validating Vehicle Probe Data.* University of Maryland. Bluetooth Summit, Houston, TX, February 2010.

12. *INRIX Traffic Blog*. www.inrixtrafficblog.com. Accessed October 9, 2012.

13. Deshpande, R., N.H. Gartner, and M.L. Zarrillo. Urban Street Performance, Level of Service and Quality of Progression Analysis. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2173, Transportation Research Board of the National Academies, Washington, DC, 2010, pp. 57-63.

14. *Traffic Signal Timing Manual.* Federal Highway Administration, Washington, DC, 2009.

15. *City of Champaign Manual of Practice, Chapter 14: Traffic Signal Standards.* City of Champaign, Champaign, IL, 2002.