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Evaluating Arterial Congestion and Travel Time Reliability Performance

Galen T. Smith
University of Kentucky, gtsm222@g.uky.edu
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Galen T. Smith, Student

Dr. Mei Chen, Major Professor

Dr. Y.T. Wang, Director of Graduate Studies

EVALUATING ARTERIAL CONGESTION AND TRAVEL TIME RELIABILITY PERFORMANCE

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science In Civil Engineering
in the College of Engineering
at the University of Kentucky

By: Galen T. M. Smith

Lexington, Kentucky

Director: Dr. Mei Chen, Professor of Transportation Engineering

Lexington, Kentucky

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ABSTRACT OF THESIS

EVALUATING ARTERIAL CONGESTION AND TRAVEL TIME RELIABILITY PERFORMANCE

This thesis presents an investigation of arterial travel time and reliability. Specifically an examination of the proposed arterial travel time reliability performance measures detailed in Federal Highway Administration's *Notice of Proposed Rulemaking* on national performance management measures are performed. These measures, including level of travel time reliability and peak hour travel time ratio, are computed and compared to those currently used to quantify congestion and travel time reliability. Within this process several commonly used data sources are evaluated to determine the effects of data quality and data source on performance measure evaluation. The newly created *Urban Streets Reliability* tool is also evaluated for its ability to estimate the effect of several proposed projects on the travel time reliability of a transportation network. In conclusion, this thesis found that the proposed travel time reliability performance measures show definite differences in estimates of facility reliability as compared with currently used performance measures such as travel time index and planning time index. A variation in the magnitude of this difference was also observed based on a rural vs. urban roadway setting. Finally, further areas of research involving the use of the *Urban Streets Reliability* tool to estimate the impact of reliability improvements on side streets and the transportation network as a whole are discussed.

KEYWORDS: Arterial Travel Time Reliability, Highway Performance Measures, Level of Travel Time Reliability, Peak Hour Travel Time Ratio

Galen Tanner Moody Smith

June 29,2016

EVALUATING ARTERIAL CONGESTION AND TRAVEL TIME RELIABILITY PERFORMANCE

By

Galen T.M. Smith

Dr. Mei Chen

Director of Thesis

Dr. Y.T. Wang

Director of Graduate Studies

June 29, 2016

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CHAPTER 1 INTRODUCTION

Travel time reliability has gained an ever-increasing role in transportation engineering today. While traditionally examined in the freeway setting, arterial travel time reliability has recently gained attention. With the passing of the *Moving Ahead for Progress in the 21st Century Act* (MAP-21) the National Highway System was expanded to include all urban arterial roadways. As such state agencies and local MPOs will now be responsible for reporting arterial performance measures to the FHWA. These performance measures must be reported on a regular basis and are measured against a target performance measure for each roadway. This rulemaking goes into effect on June 15, 2018.

Despite the increased attention and new rulemaking there is currently little research dealing with arterial travel time reliability performance as compared to the freeway setting. This is due to the numerous challenges presented when attempting to quantify arterial roadway reliability performance. For example, reliability performance measurement requires large amount data that is often lacking on arterial roadways due to the low volumes as compared to freeways. Furthermore, there is currently no accepted method of practice for integrating reliability performance measures into project planning and decision-making.

This thesis offers an examination of traditional travel time reliability and congestion performance measures and their applications to urban and rural arterial roadways as well as new methodology for incorporating reliability performance measures into transportation decision making.

1.1 Literature Review

As arterial travel time reliability is a relatively new field in the area of transportation engineering there is currently no standardized practice for arterial travel time reliability measurement. Due to the challenges of obtaining the necessary data items and the issues associated with the data explained here, few lines of research have been advanced in the field so far. What follows is an examination of the more prominent lines of research into travel time reliability relating to both arterial and freeway locations.

Research into the field of travel time reliability began with Prashker *(9)* who in the early 1980s used attitudinal surveys to identify the measures of reliability that were most important to users of the transportation system in the Chicago area. He determined that at the time in-vehicle reliability was less important to the average traveler than out-of-vehicle reliability issues such as finding parking.

Since then travel time reliability has evolved significantly. Jin and Mcleod for example compared several travel time reliability measures using spot speed data on Florida freeways *(5).* The authors determined that the 90th percentile travel time index is the most consistent and sensitive reliability metric for Florida freeways.

Day et.al *(1)* examined arterial routes in the state of Indiana. The authors used aggregated 15-minute period speed data to quantify arterial reliability on 28 arterials containing 341 signalized intersections in the state of Indiana. They determined that with increasing signal density on arterial roadways travel time increases and reliability decreases. It should be noted that similar to the *NPRM* methodology the authors replaced any missing or null speed records with the posted speed limit on the arterial.

Eisele et. Al. prepared a compendium of the lessons learned by transportation agencies as they prepare for the MAP-21 proposed performance measures *(3).* The authors examine commonly used arterial performance metrics such as the travel time index, buffer index, and planning time index finding that the buffer index is too unstable for use in reporting arterial reliability. Furthermore, the authors examine various metrics to be used as the reference speed in performance measure calculation finding the uncongested speed (not to exceed posted speed limit) most accurately reflects the baseline condition for delay estimation on a facility. The authors defined this uncongested speed as the speed during the early morning or late night hours when congestion is not present on the facility. The authors also present adapted performance measure target speed values as a baseline value for use in performance measure calculation.

Fartash, Hadi, and Xiao, examined the accuracy of the *Highway Capacity Manual 2010* urban street methodology to estimate travel speed and travel time on arterial roadways in Florida during differing levels of rain events *(4)*. The methodology was examined through the use of the SHRP2 project L08's STREETVAL analysis tool. Through the use of differing values of saturation flow rate and free-flow speed the authors were able to determine that under no rain conditions the saturation flow rate value of 1900 vphpl produced the best estimated travel time data as compared to the measured. Furthermore, the authors found that when using the urban streets methodology for real-time travel time prediction, forecasted demands produced the best results as compared to use of instantaneous demands and typical day demands as inputs to the methodology.

Sun, Liu, Peng, and Ni developed a new congestion indicator for use in reflecting congestion conditions on urban arterials using speed data from arterial roadways in Changzhou, China as a case study *(10).* The authors developed the average congestion index (ACI) based on the flow rate present on each link of a transportation network and the link's congestion index (CI) to represent congestion levels on an arterial facility as a whole. Using speed data from the case study the authors validated the use of the ACI by determining a positive correlation between congestion and the proposed metric.

Young examined the use of Bluetooth and probe vehicle data for calculating arterial performance measures in *(14)* finding that as probe vehicle data becomes more sparse, delay is underestimated on a facility. Furthermore, Young proposed that principal arterial roadways are likely to have usable probe vehicle data whereas minor arterials and collectors are more likely to lack usable data due to the decrease in AADT across each facility type.

1.2 Research Objectives

Following along with the line of thought utilized by the researchers listed above, several performance measures and data sources are examined herein for their ability to accurately detail conditions on an arterial facility. Among the performance measures examined are travel time index (TTI), planning time index (PTI), travel speed, and the new measures proposed by the *Notice of Proposed Rulemaking*. These measures will be examined for the first time with the objectives of determining if the proposed performance measures are able to give a similar picture of travel time reliability compared to the currently accepted performance measures when applied to the same segment of arterial roadway.

The inclusion of reliability and congestion performance measures into transportation project planning will be addressed through the use of estimated traffic speed and travel time data as generated by the new *Urban Streets Reliability Module* of the current *Highway Capacity Software 2010* project suite. This module allows the estimation of future arterial traffic speed and travel time data based on current measured data. This allows the estimation of future performance measures after project implementation. The estimated data along with data that has been adjusted using the proposed methodology found in the *NPRM* will be examined within to the utility of each data type in estimating performance measures on a facility.

The tests detailed above will be conducted using measured and estimated data on two urban and one rural arterial sites in Kentucky. These are US-231 Scottsville Road in Bowling Green, US-31W Dixie Highway near Elizabethtown, and a more rural section of US-31W near Radcliffe. Performance measures will be compared based on measured and estimated data, conclusions will be drawn about how each performance measures detail conditions on the facility, and finally areas of future research and interest related to arterial reliability will be addressed.

CHAPTER 2 ISSUES AND COMPLEXITY OF ARTERIAL PERFORMANCE MEASUREMENT

2.1 Current Reliability and Congestion Performance Measures

Currently there are several reliability and congestion performance measures that are generally accepted in the engineering field for use with arterial roadways. Eisele, et al. *(3)* performed a review of lessons learned while preparing for the MAP-21 performance measures and determined that there is no single measure that can identify all aspects of reliability and mobility. Despite this they were able to compile a list of the most meaningful reliability performance measures as used by engineering professionals; the travel time index, planning time index, and buffer index.

Travel time index is defined as the ratio of peak period travel time to reference or free-flow travel time *(3)*. The travel time index or TTI can be calculated using equation 1.

$$\text{Travel Time Index} = \frac{\text{Peak Period Travel Time}}{\text{Free Flow Travel Time}} \quad (1)$$

The travel time index is used to quantify congestion on a facility and gives a measure of how well traffic is flowing as compared to the peak period. Peak period is defined as the hours of 6-9AM (6:00-9:00) and 3-6PM (14:00-17:00). In the case of arterial roadways, the free-flow speed is often defined as the uncongested speed or speed that travelers attain during periods of light traffic *(3)* not to exceed the posted speed limit. As measured data is often scarce on arterial facilities the speed limit is often used as the free-flow speed in place of uncongested measured speeds. This in turn makes the free-flow travel time equal to the travel time when traveling at the speed limit.

Planning time index is defined as the extra time that should be allocated to a trip to arrive on-time at a destination 19 out of 20 times *(3)*. The planning time index or PTI can be calculated using equation 2.

$$\text{Planning Time Index (PTI)} = \frac{\text{95th Percentile Travel Time}}{\text{Free Flow Travel Time}} \quad (2)$$

Similar to the travel time index the free-flow speed used in the planning time index calculation is defined to be travel time when traveling at the speed limit. Planning time index is a measure of the reliability of a facility that is easily communicable to the general public. A PTI of 1.2 for example means that an extra 20% of travel time should be added on to a trip to ensure arrival 19 out of 20 times.

The buffer index is defined as the difference in the 95th percentile travel time and average travel time divided by the average travel time *(8)*. The buffer index can be calculated using equation 3.

$$\text{Buffer Index (BI)} = \frac{\text{95th Percentile Travel Time - Average Travel Time}}{\text{Average Travel Time}} \quad (3)$$

The buffer index represents the time that a traveler must add-on to their average travel time to ensure on time arrival at a destination 95 % of the time. Usually expressed as a percentage, the buffer index can be multiplied by the average travel time to arrive at a value of extra travel time that must be allocated.

A fourth measure of reliability known as the reliability index was proposed by the AASHTO Task Force on Performance Measure Development, Coordination, and Reporting *(3)*. This measure was defined as the ratio of the 80th percentile travel time to the reference travel time threshold. The reliability index can be calculated using equation 4.

$$\text{Reliability Index (RI)} = \frac{\text{80th Percentile Travel Time}}{\text{Reference Travel Time}} \quad (4)$$

Note that when the free-flow travel time is used as the reference travel time the reliability index is equivalent to the planning time index when using the 80th rather than 95th percentile speed.

2.2 MAP-21 Proposed Performance Measures

As part of the MAP-21 directive the *Notice of Proposed Rule Making* introduced new performance measures for quantifying the performance of arterial roadways. These are "level of travel time reliability" (LOTTR) and "peak hour travel time ratio" (PHTTR) *(6)*.

The level of travel time reliability is defined to be the ratio of the 80th percentile travel time to the 50th percentile travel time *(6)*. The metric is to be calculated for four time blocks; 6:00 to 10:00 AM (6:00-10:00), 10:00AM to 4:00 PM (10:00-16:00), and 4:00 to 8:00 PM (16:00-20:00) on weekdays. For weekends the metric would be calculated for the period of 6:00AM to 8:00PM (6:00-20:00). The level of travel time reliability can be found using equation 5.

$$\text{Level of Travel Time Reliability (LOTTR)} = \frac{\text{80th Percentile Travel Time}}{\text{50th Percentile Travel Time}} \quad (5)$$

As a threshold value, the *NPRM* states that a segment reporting a LOTTR that is less than 1.50 for all time periods would be providing reliable travel times to all travelers. Any null or missing travel time values are to be replaced with travel times when traveling at the speed limit in the LOTTR calculations.

The peak hour travel time ratio (PHTTR) is defined to be the ratio of the peak hour travel time to the desired peak hour travel time. This metric is proposed for use in urbanized areas with populations over one million. The peak hour travel time ratio can be calculated using equation 6.

$$\text{Peak Hour Travel Time Ratio} = \frac{\text{Peak Period Travel Time}}{\text{Desired Peak Period Travel Time}} \quad (6)$$

This metric is to be found for the time blocks of 6:00 to 9:00 AM (6:00-9:00) and 4:00 to 7:00 PM (16:00-19:00). All travel times which correspond to speeds less than 2 mph and greater than 100 mph are to be removed before calculation. The measured peak hour travel times used when calculating the PHTTR are the highest numeric value annual average travel time among the peak hour blocks discussed above. It is the job of the reporting agency to determine the desired peak hour travel time for use with the PHTTR. Similar to the LOTTR the threshold value for the PHTTR is set to 1.50 where segments reporting a value less than this are considered to be meeting expectations *(6)*.

The desired speed value (used to determine the desired travel time used as the denominator in the PHTTR equation) is to be set by the reporting agency. As the notion of desired speed is a new concept in the field of transportation there is currently no prevailing method of determining this value. For the desired peak period travel time used in this study, percent of prevailing light traffic values were adopted from a study by Turner *(11)* who categorized performance measure target speed values based on intersection density. Turner found these values by adjusting the percent of free-flow speed values used by the *HCM 2010* to determine each LOS for the effect of signalized intersections on traffic flow. These values are summarized in Table 5.These speed-density relationships were adopted for use when determining the desired peak period travel time. For the purposes of this research the speed limit on the facility was substituted in place of the prevailing light traffic speed as in all cases the speed records during the early morning and late night hours when prevailing light traffic occurs were few.

Table 1: Turner Performance Measure Target Speed Values

Intersection Density (Intersections per mile)	Target Value = Percent of Prevailing Light Traffic Speed
<2	100
2 to 4	90
4 to 8	85
More than 8	75

2.3 Data Sources

Before any performance measure calculation can take place an analyst must have measured speed or travel time data for their subject facility. In the case of arterials this data may come from a variety of sources. While some sources may contain more data than others, each has value. This section gives a short discussion of each data source commonly available on arterial roadways noting the specific advantages and disadvantages of using each.

2.3.1 GPS Based Probe Vehicle Data

Probe vehicle data is widely available today due to the increased popularity of GPS equipment in recent years. Using this GPS technology vehicles self-report their position and speed on a network. Individual vehicle readings taken during the same time interval are then aggregated together to produce an overall speed profile for traffic during that interval. Probe data is advantageous in that it most often covers large portions of the network spatially and is readily available from private data vendors such as INRIX and HERE.

However, while probe vehicle data normally contains good spatial coverage, temporal coverage on a network is often lacking. This is especially true on arterial roadways which often lack significant volume during the early morning and late night hours. This may cause inaccuracies in the speed records at these time periods as a recorded speed may be based on only a single probe vehicle. Furthermore, as the data is GPS based, vehicles that are stopped or idle may be recorded on the network. These vehicles produce speed records of 1kph (0.621 mph), which may significantly affect the average speed during a time period in the late night and early morning hours, may be the only speed recorded.

2.3.2 Bluetooth Data

Another readily available data source is Bluetooth reader data. Bluetooth speed records are sensor based and are determined using the Bluetooth ID of a passing vehicle. When the vehicle passes the first sensor of a sensor pair this Bluetooth ID is recorded. When the vehicle then passes the second sensor its Bluetooth ID is recorded again and a travel time between the two sensors is determined by ID matching. With a known distance between sensors the speed is then determined as the distance divided by the travel time. This data offers advantages as readers may be placed where desired and vehicles are only recorded when the trip between two sensors is complete. This eliminates the idle vehicle records from the speed data.

There are also disadvantages when using Bluetooth records. As the data readers cover a large (500ft for KYTC Bluetooth readers) radius it is possible for travelers on roadways running parallel to the subject facility to be recorded by a Bluetooth reader on the facility in question. This may lead to inaccuracies in the measured Bluetooth data where one or more arterial roadways of differing conditions are closely spaced. The total number of speed records also becomes an issue when dealing with Bluetooth data as far fewer travelers use Bluetooth while driving as compared to GPS equipment.

2.3.3 NPMRDS Data

The National Performance Management Research Data Set (NPRMDS) is another form of probe data that differs from the private vendor data in many ways. First and foremost, the NPMRDS dataset is specified by the FHWA to report no smoothing, filtering, or imputation of measured speed data *(7).* Data is recorded in 5-minute intervals and attached to roadway segments known as TMCs or traffic message channels. This data is also probe vehicle based using the national highway system as a basis. As many national highway system roadways are classified as arterials this data source contains mostly arterial roadway data. This also means that the NPRMDS network lacks much of the coverage of other data sources as lower functional class roadways may not be present in the network. The data comes in the form of travel times across each TMC segment.

Similar to the Bluetooth and Private vendor data there are numerous advantages and disadvantages to the NPMRDS dataset. This data is advantageous when working with arterial performance measures as it contains data for both trucks and passenger cars separately. The separation of these two datasets allows separate metrics to be found for each vehicle type. The disadvantages of the data include the lack of spatial coverage and the length of the TMCs to which the data is attached. Spatial coverage of the dataset becomes an issue when dealing with arterial roadways as many arterials (such as US-231 Scottsville Road) have very poor TMC coverage across their whole length. The length of the TMC links also becomes an issue as larger TMCs cause a lack of fine resolution in the data. When a single TMC spans multiple urban street segments for example it is impossible to analyze the individual segments between intersections that make up the TMC as a whole.

2.4 Project Locations and Reliability Issues

As stated above three arterial segments were selected for performance measure calculation. What follows is an overview of each site and the congestion and reliability issues associated with each.

2.4.1 US-231 Scottsville Road

The US-231 network comprises the US-231 segment of Scottsville Road in Bowling Green, KY terminating at Lover's Lane (where the US-231X designation begins). The facility contains 6 signalized intersections bounding 5 urban street segments. This portion of the facility is heavily urbanized and commercialized containing many restaurants and shopping venues. Numerous unsignalized access points exist along the facility ranging from private driveways to the large Greenwood Mall Entrance. The US-231 facility is shown in Figure 1 .

The reliability and congestion issues experienced at this site are a result of the large commercialization of the surrounding area. Due to the large number of restaurants and commercial shopping locations present the facility experiences far higher volume than would be present solely with commuter use. Figure 3 and Figure

4 present aerial photos showing the high restaurant and commercial establishment density on areas of the US-231 facility.

The proximity to Western Kentucky University also presents issues for the facility. When the WKU campus is in session far larger volumes are seen on the facility during the Friday-Sunday period due to the numerous special events held during these days.

Information obtained from local transportation cabinet officials purported that Friday was the worst day of the week in terms of congestion. This is due to both Friday being considered to be the first day of the weekend causing a large draw of local residents to the areas restaurants. Furthermore, most restaurants along the facility receive deliveries on Friday. This influx of large fleet vehicles further serves to destabilize the traffic flows in the area. The WKU campus also contributes to this phenomenon as many students seek to leave campus to return home after the conclusion of classes on Friday.

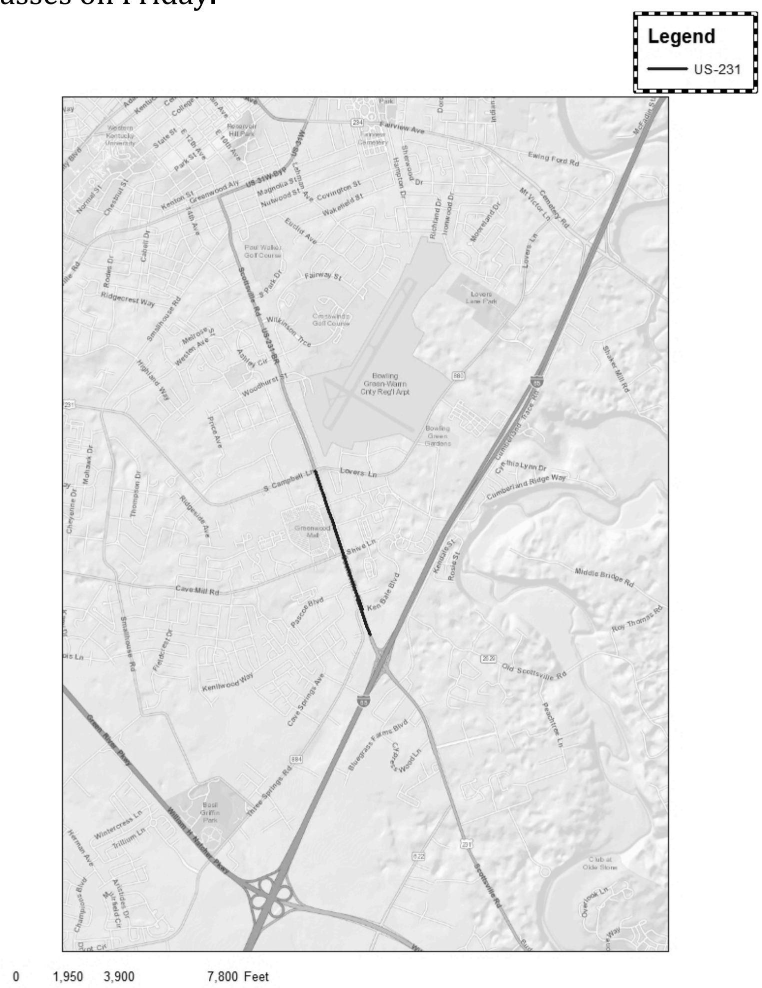


Figure 1: US-231 Scottsville Road Bowling Green, Kentucky

Figure 2: Aerial Photo of US-231 at Pascoe Blvd

Figure 3: Aerial Photo of US-231 at Bryant Way

2.4.2 US-31W Dixie Highway

Two sections of US-31W are used for this analysis. The first segment (covering the high signal density portion of US-31W) is a more urbanized arterial segment running from Ring Rd to Town Drive near Elizabethtown, KY. This segment contains three signals and is approximately 0.4 miles long. The second segment (covering the low density portion of US-31W) encompasses a more rural area running from Centennial Drive to KY-144 near Radcliffe, KY. This segment also contains three signalized intersections and is approximately 1.2 miles long. These segments are shown in Figure 4. Figure 5 and Figure 6 present aerial photos of each location respectively detailing the land use surrounding each segment of the facility.

Each segment of the US-31W facility experiences differing reliability issues. The high-density segment is surrounded by a more urbanized area and experiences large delays due to the high density of signalized intersections. Due to this high density in such a small distance vehicles experience excessive travel times when stopped by a red signal indication but very low travel times when all signals are green. This causes great discrepancy in the travel times along this segment of the facility and as a result lower travel time reliability.

The low-density segment of this facility in a more rural area than the high-density portion. This segment of the facility has numerous unsignalized access points in the form of private driveways and a two-way left turn lane (open median) allowing vehicles to move across opposing traffic. These private drives cause delays in the normal traffic flow as vehicles attempt to move across oncoming traffic to enter a private drive or business entrance.

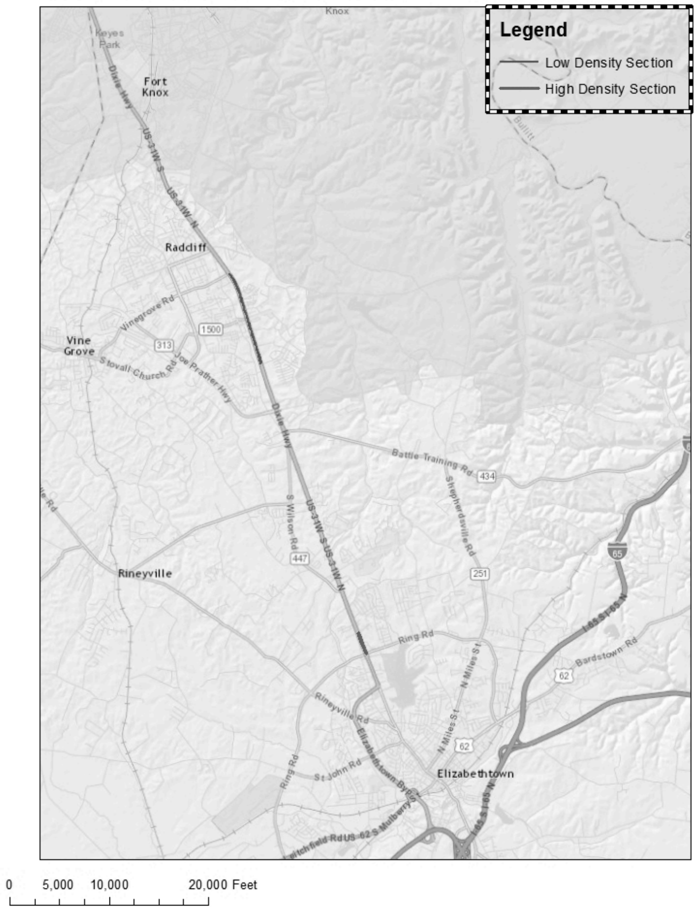


Figure 4: US-31W Network Segments

Figure 5: Aerial Photo of US-31W High Density Area

Figure 6: Aerial Photo of US-31W Low Density Area

2.4.3 Available Data Sources

Probe vehicle data was purchased for all sites used herein from the HERE private data vendor. The HERE data was made available for this project beginning with year 2012 and continuing to year 2014. The data is GPS based and record probe vehicle speeds as probes travel along defined segments of roadway called links. The data arrived in 15-minute intervals in the kph format. During the data quality control process speeds were converted to mph for ease of understanding. Speeds of 0 mph and excessively low speeds of <5 mph were considered outliers that may have resulted from a single probe vehicle. As the data arrived in 5-minute time intervals, when the aggregation to 15-minute periods was completed these data outliers were removed.

Bluetooth data for this project was made available through the Kentucky Transportation Cabinet. Bluetooth data for the facilities under study became available starting in 2012 and up to 2014.

2.5 Determining Reference Speeds

Before any performance measure calculations could take place a reference speed (to be used as the benchmark speed) was needed. Currently there are several accepted methods of determining the free-flow speed on a facility. The three most commonly used measures of FFS are the 85th percentile travel speed, the uncongested speeds on a facility during light traffic hours (early AM and late PM), and the posted speed limit. However, there are issues associated with using each of these measures.

A study by Chen and Zhang *(16)* determined that congestion may be overestimated when using the 85th percentile speed on facilities with low speed limits. When dealing with facilities with higher posted speed limits the authors found that the 85th percentile speed is most often below the posted speed limit. The same study found that using nighttime speeds for estimation of day time congestion levels led to overestimates of congestion on a facility.

Eisele, et. al *(3)* preferred the use of the uncongested speed (not to exceed the posted speed limit) as the free-flow speed but determined that this speed should ideally be calculated based on one full year of continuous data. In the absence of a continuous data source the authors recommend the use of posted speed limit or a percentage of posted speed limit be used. The same study also cautions against the use of the speed limit in cases where speed limits change from year to year and across facilities noting that posted speed limits are sometimes affected by public policy. A further measure of threshold speed is proposed by the authors. This involves setting a threshold speed (20 mph on arterials for example) for use in states as a whole or the areas surrounding a project.

Another possible measure of FFS is the based on the urban street classifications presented in the *HCM 2000.* These definitions categorized urban streets based on intended street function and signalized intersection density. The resulting FFS values range from 50mph for class I facilities to 30 mph for class IV facilities.

While there are numerous methods available of determining the reference speed which method to use is ultimately up to the reporting agency. As such many performance measures are not directly comparable across different facilities or when obtained from different reporting agencies.

As a starting point toward determining the proper reference speed in this research for each network the measured speed cumulative density function (CDF) for each network was created. In the case of US-231 this is based on both Bluetooth and HERE data. The CDF for each of the US-31W sites is based on HERE data only as the Bluetooth reader locations did not allow for any aggregation of the data to properly represent the segments of US-31W chosen for use.

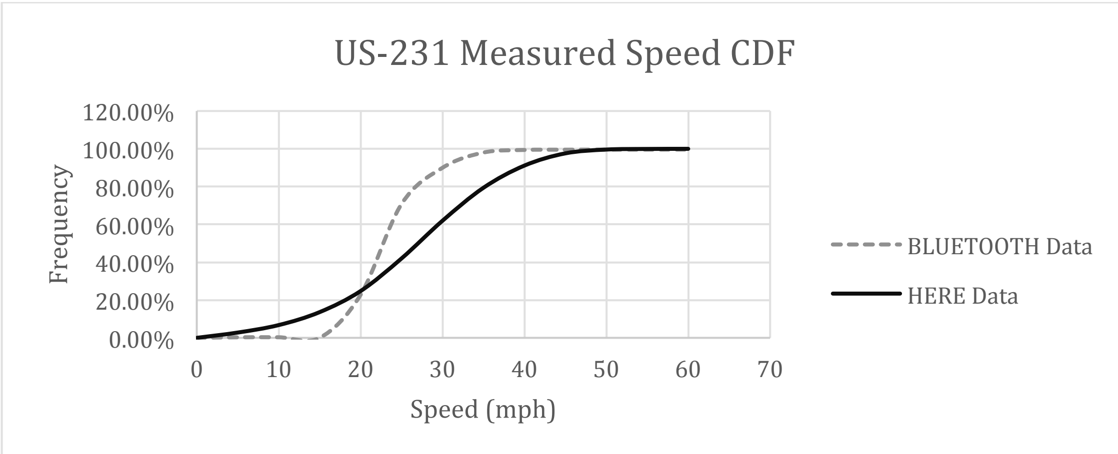


Figure 7: US-231 Measured Speed CDF

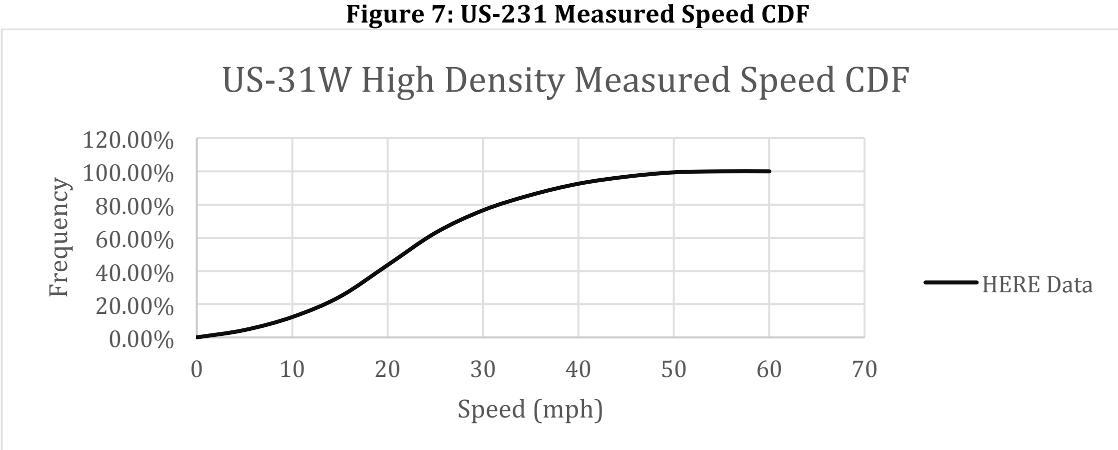


Figure 8: US-31W High Density Measured CDF

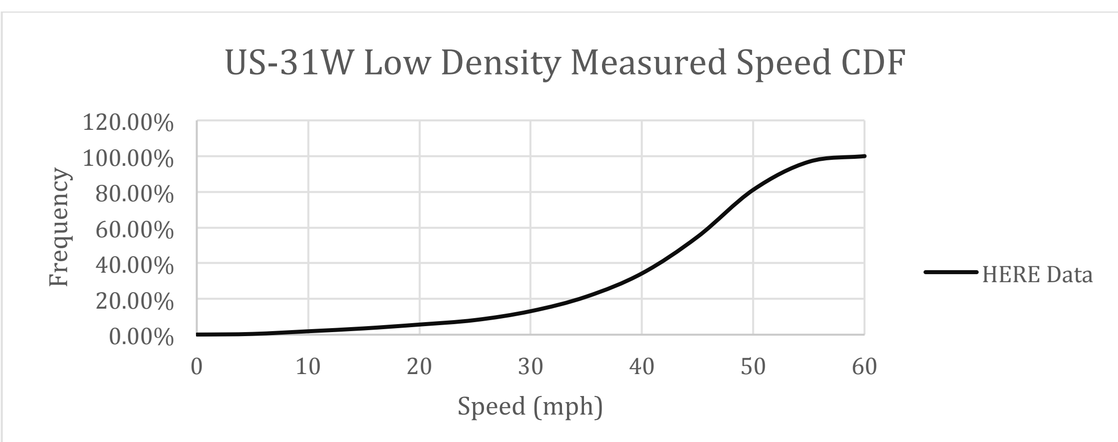


Figure 9: US-31W Low Density Measured Speed CDF

From Figure 7 the 85th percentile speed as determined using the Bluetooth data is approximately 28 mph. Using the HERE data this speed climbs to approximately 38 mph. It should be noted that both data sources contain nearly the same number of readings (12,418 HERE data readings, 12,328 Bluetooth readings). As these speed records are reported in 15-minute intervals this is a fairly low number of records (35,040 15-minute periods within a year). The discrepancy between the two data sources may be attributed to two sources. First is the sample size that was used to determine the average speed during each 15-minute analysis interval. In the case of the KYTC Bluetooth data this sample size is typically very low (1-10 probe vehicles per 15-minute period) whereas in the case of the HERE data this sample size was not made available with the 2013 data. Second is the time of day distribution of the data. Bluetooth data for example is most available during the daytime hours when higher volumes mean a higher probability of a traveler using a Bluetooth device passing a reader. As we can see in Figure 10 below both the Bluetooth and HERE data have significantly more readings during the daytime hours than either early morning or late night.

Referring back to Figure 8 and Figure 9 the high density portion of US-31W shows an 85th percentile speed of 35 mph (below the posted speed limit of 45 mph) while the low density portion shows an 85th percentile speed approximately equal to the speed limit (55mph). This is consistent with the findings of Chen and Zhang detailed above (that facilities with a high posted speed limit have 85th percentile speeds at or below the speed limit).

Caution should be used when considering the use of these measured 85th percentile speeds as the FFS. This is because most speeds records obtained from both data sources are recorded during the period from the AM peak to the PM peak hours. This leaves large portions of the 24-hour day, specifically the late night and early morning hours with few readings. These late night and early morning hours are the hours when most travelers are able to traverse the facility under light traffic conditions. With the exclusion of this data from the CDF calculations the 85th percentile speeds become lowered toward the speed values represented during the AM and PM peak hours when most readings occur. To confirm this theory examination of the number of measured speed records of each data source throughout the day were conducted. In the US-231 case the data was received in a format in which only 15-minute periods with measured speeds were given. This allowed the direct calculation of number of records across the whole 2013 year from the raw data. Note that this comparison is conducted for the cardinal (NB) direction.

For the case of the US-31W site, the HERE data was received in the month_day combined format for each link of the HERE network contained within the US-31W facility. As such it was necessary to conflate the individual link speeds to a segment wide (for the two segments under study) space mean speed before the total number of speed records was examined. The US-231 HERE data in contrast arrived in single day format with each speed record corresponding to a 15-minute analysis period during a discrete day of the year. The Bluetooth data arrived in a similar day by day format on the US-231 site. As the Bluetooth data needs no aggregation and was received in a corridor wide format originally we should expect to see more speed records present than in the HERE data. This is confirmed by Figure 10. The frequency of the speed records for the US-31W network is also examined in Figure 11 and Figure 12.

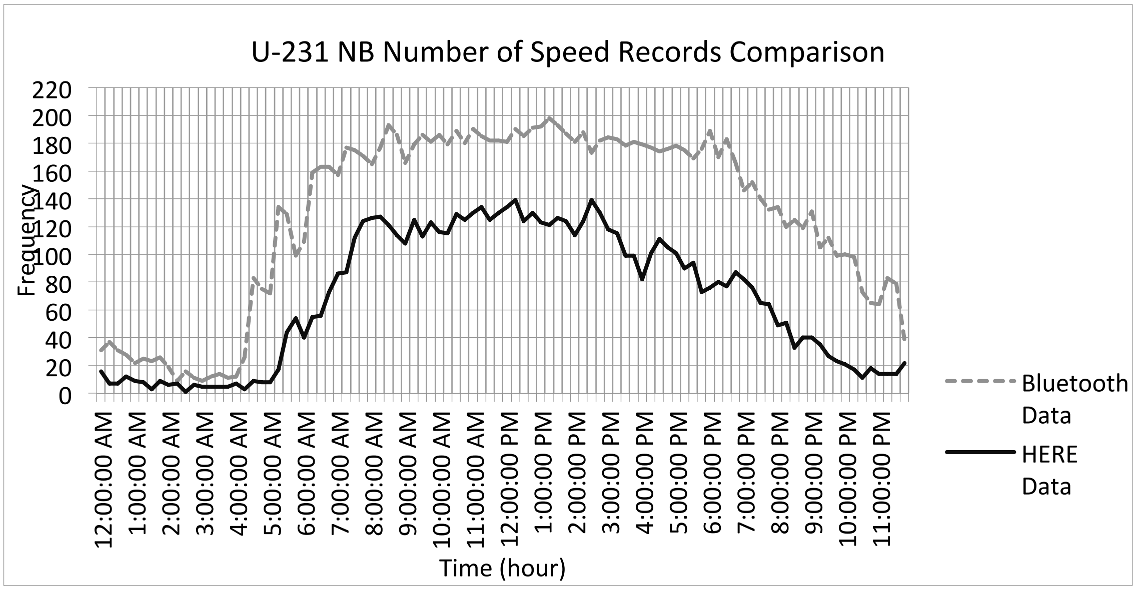


Figure 10: US-231 Speed Records Comparison

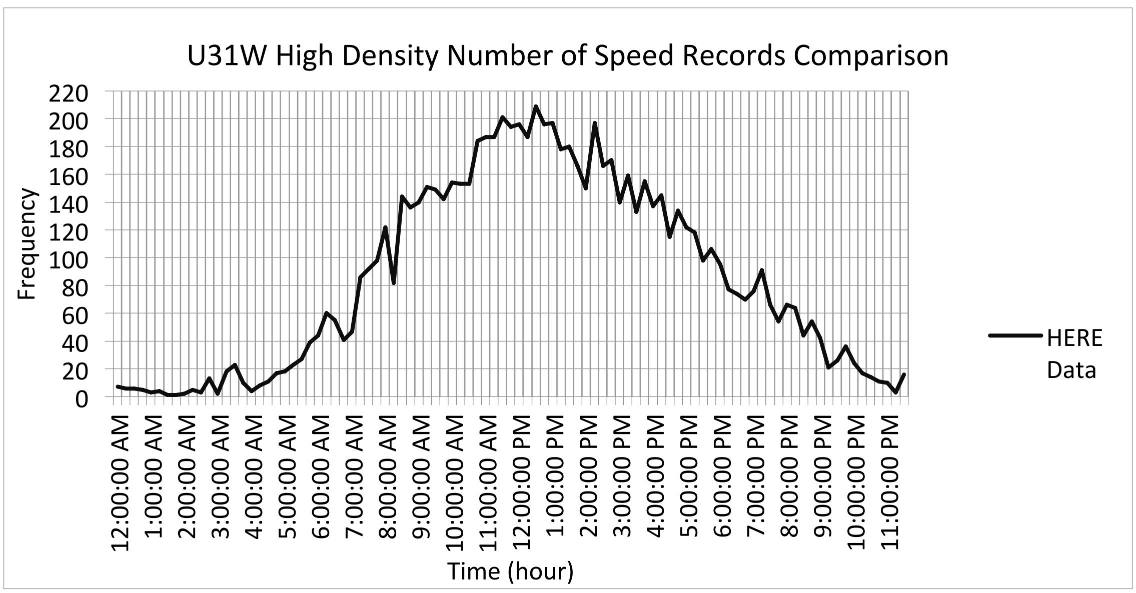


Figure 11: US-31W High Density NB Speed Records Comparison

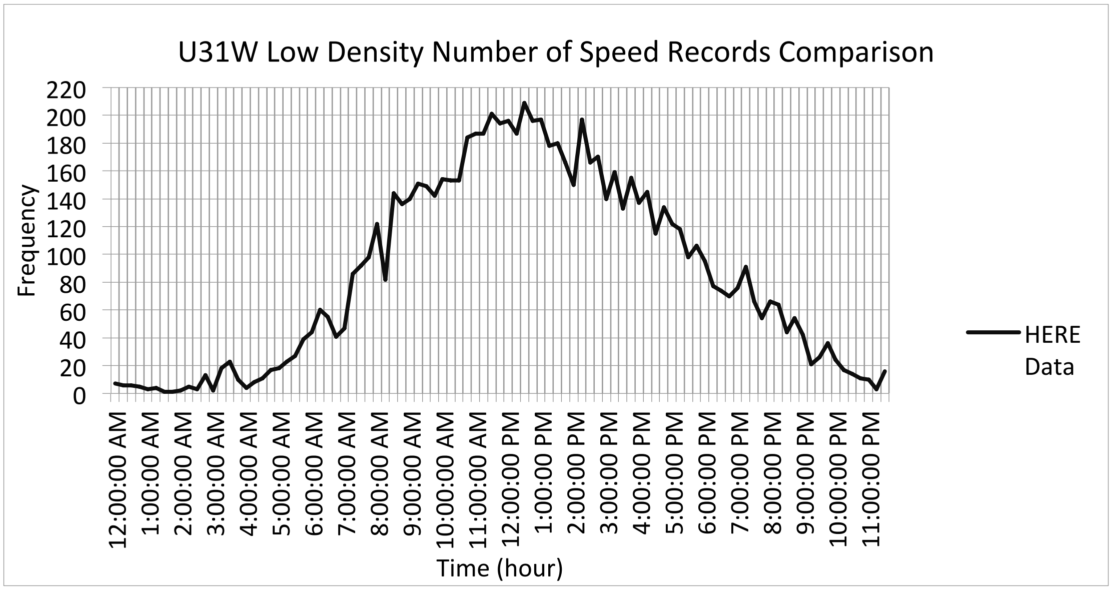


Figure 12: US-31W Low Density NB Speed Records Comparison

It should be noted that the frequency of the speed records decreases significantly during the hours after the PM peak period and before the AM peak period. These missing data points lower the 85th percentile speed toward the lower speed values attained during the peak period when there are more speed records. As a means of removing this bias from the analysis the speed limit (the most stable measure of reference speed) is selected from the other methods of determining free-flow speed for use in this research.

2.6 Performance Measure Comparison Using Measured Data

In order to examine the ability of the *NPRM* proposed performance measures to present conditions on a facility, a comparison of these measures (and the proposed methodology for data quality control contained in the *NPRM)* to currently used performance measures was conducted. Only performance measures that offered a clear, concise view of reliability and congestion were considered for use. Of the 4 currently accepted performance measures detailed above the buffer index was not considered for advancement. This was because the SHRP2-Project L03 *(8)* found in their final report that the buffer index could produce counterintuitive results by indicating lessened congestion but worsened reliability.

The reliability index was also not selected for use, as it is the equivalent to the planning time index when calculated with the 80th percentile travel time rather than the 95th percentile.

This leaves the travel time index and planning time index accepted for comparison to the proposed performance measures. Both TTI and PTI are commonly used measures in the field of transportation engineering. Both are unit-less measures based on the free-flow speed meaning that comparisons between different segments of the same facility with differing characteristics are possible.

LOTTR is also comparable to the currently accepted performance measures in that a facility would indicate a high level of travel time reliability during periods where the planning time index remains relatively stable. Fluctuations in the PTI would in turn mean travelers on a facility need to budget different amounts of extra travel time during different periods of the day indicating an un-reliable facility.

2.6.1 Equating TTI and PHTTR to LOS

PHTTR although similar to TTI, is not directly comparable to any currently accepted performance measure. As such both PHTTR and TTI were equated to a commonly used, easily communicated, qualitative performance measure, level of service (LOS). By doing so both performance measures could be compared with respect to the LOS each indicated on a subject facility.

Level of service categories on urban arterials are classified by the *HCM 2010* to be a percentage of free-flow speed achieved on the facility. The boundary speeds are contained in *HCM 2010* Exhibit 16-4 and can be seen in Table 2.

Table 2: LOS Boundary Speed

LOS	% of FFS
A	85
B	67-85
C	50-67
D	40-50
E	30-40
F	<30

To equate the LOS to TTI and PHTTR the percentage of FFS given above were multiplied by the speed limit (used herein as the surrogate FFS) on the facility to produce boundary speeds. These speeds represent the actual travel speed experienced by travelers when the facility is operating under each LOS. These boundary speeds were then used to determine the travel time values corresponding to each LOS boundary. These travel times were used as measured travel time inputs to the PHTTR and TTI equations producing a value of each performance measure when traveling at the LOS boundary speeds.

For example, the speed limit on the US-231 facility is recorded as 45 mph. Using the TTI equation and a measured speed value of 0.85*45mph = 38 mph is obtained. This 38 mph is then used to calculate the measured travel time input to the TTI equation. The result is a TTI value, which corresponds to LOS A on the facility. This process is shown in equation 7.

$$TTI_A = \frac{\text{Travel Time}_{85}}{\text{Free Flow Travel Time}} \quad (7)$$

where;

$$TTI_A = \text{TTI corresponding to LOS A}$$

$$\text{Travel Time}_{85} = \text{Travel Time at 85\% of free-flow speed}$$

This process produces TTI boundary values corresponding to each LOS category. Note that Table 3 is left inclusive.

Table 3: TTI Based LOS Boundaries

LOS	TTI	
A	<1.18	
B	1.18	1.5
C	1.5	2.0
D	2.0	2.5
E	2.5	3.3
F	>3.3	

The same procedure detailed above was used to create LOS categories corresponding to a boundary PHTTR. Because each segment used in this research had differing intersection density, different PHTTR based LOS metrics were calculated for each segment. These metrics were found using the percent of prevailing light traffic speeds found in Table 5. Using the speed limit on each facility in place of prevailing light traffic speed a desired speed was found. In the case of the US-231 network for example, this desired speed was found using 1.24 miles/6 signalized intersections = 7 intersections/mile = 85% of prevailing light traffic speed = 0.85(45 mph) = 38.25 mph. These desired speeds were then used to find the desired travel time on each facility.

Table 4: PHTTR Based LOS Boundaries

PHTTR						
LOS	*Low Density US-31W*		*High Density US-31W*		*US-231*	
A	<1.18		<0.88		<1.0	
B	1.18	1.49	0.88	1.12	1.00	1.27
C	1.49	2.00	1.12	1.50	1.27	1.70
D	2.00	2.50	1.50	1.88	1.70	2.13
E	2.50	3.33	1.88	2.50	2.13	2.83
F	>3.33		>2.50		>2.83	

Note that a value of 1.50 is considered acceptable based on the *NRPM*. This corresponds to an acceptable LOS of C during the AM and PM peak period. This is reasonable as LOS C is generally considered acceptable in high-density urban areas and during peak periods on arterial roadways.

This allows comparison of the measured TTI and PHTTR values on each of the three facility segments used herein without the need to recalculate the LOS boundary conditions for each facility.

2.6.2 Examination of NPRM Speed Adjustment Methodology

Examination of the initial data sources revealed issues with both the HERE and Bluetooth data when calculating either set of performance measures. The Bluetooth reader network was too sparse and lacked the fine spatial resolution needed to calculate performance measures on either section of the US-31W site.

The HERE data presented numerous issues relating to temporal coverage. Namely, the early morning and late night hours lacked recorded speeds during most 15-minute periods. As no probe vehicle sample size was presented with the HERE data it is also unknown whether the recorded speed accurately details the average travel speed on either facility or the speed of only a few probe vehicles during that time period. Due to the large number of periods lacking data and the stipulation that a full-year aggregated dataset be used to determine the new performance measures, the *NPRM* methodology was used to complete the HERE datasets by filling in the missing speed readings with speeds equal to the speed limit.

Initially the measured speed data distributions on each facility were examined before and after the quality control methodology was implemented. This comparison was useful to determine if the *NPRM* methodology of replacing the null with speeds at the speed limit significantly affected the distribution of speeds on the facility. The measured and adjusted speed distributions on the facility can be seen in Figure 13 - Figure 18.

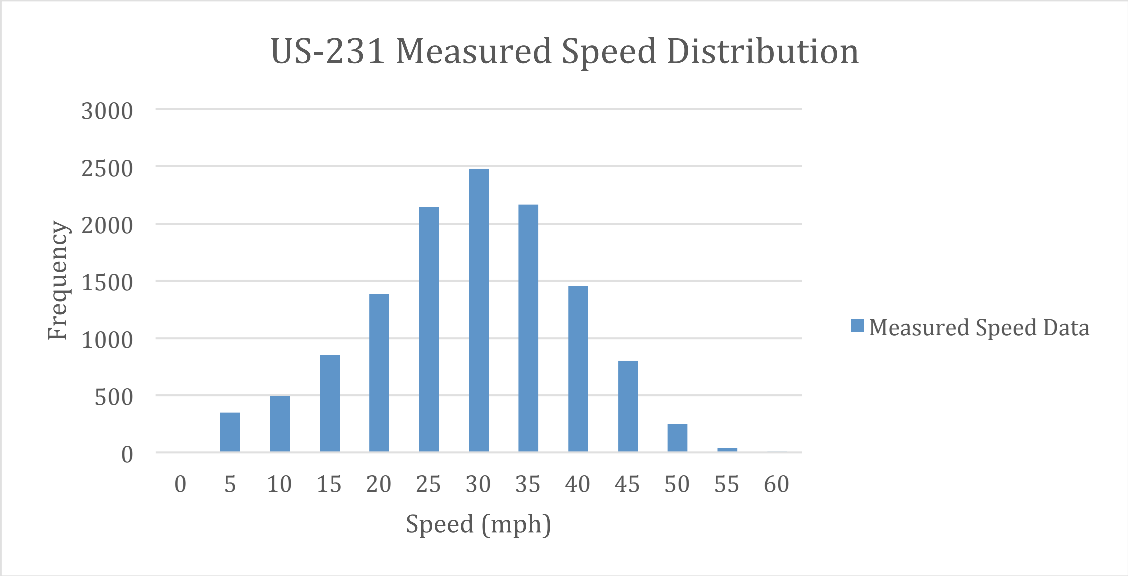


Figure 13: US-231 Weekday Measured Speed Distribution

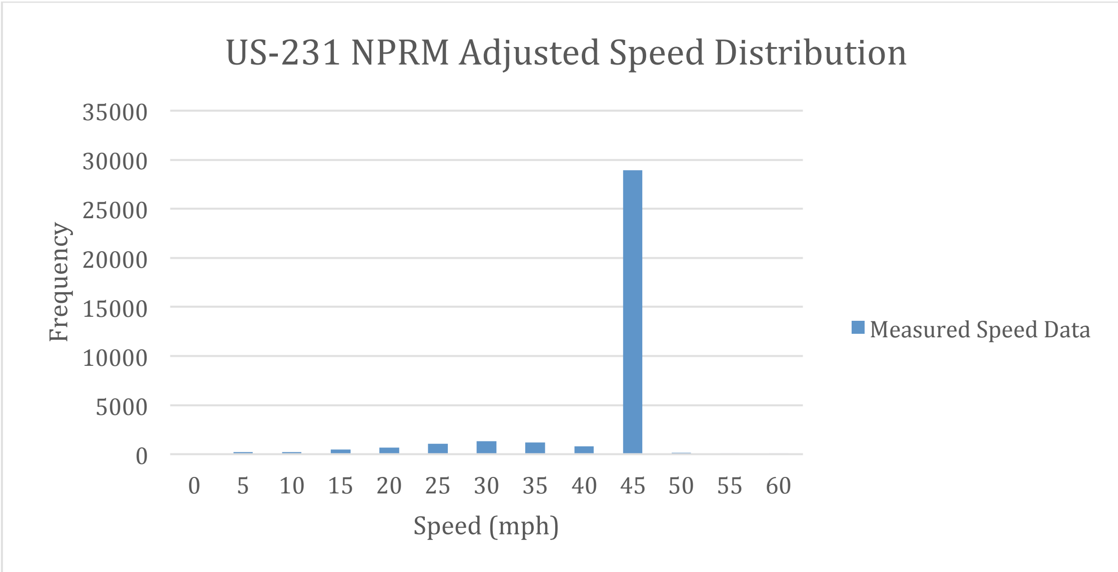


Figure 14: US-231 Weekday Adjusted Speed Distribution

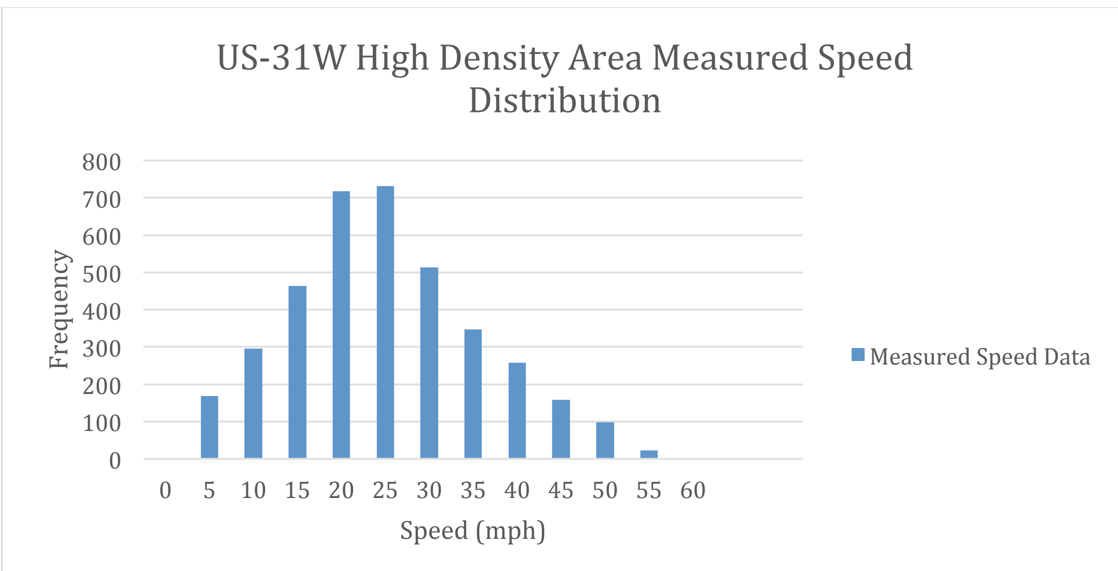


Figure 15: US-31W High Density Weekday Measured Speed Distribution

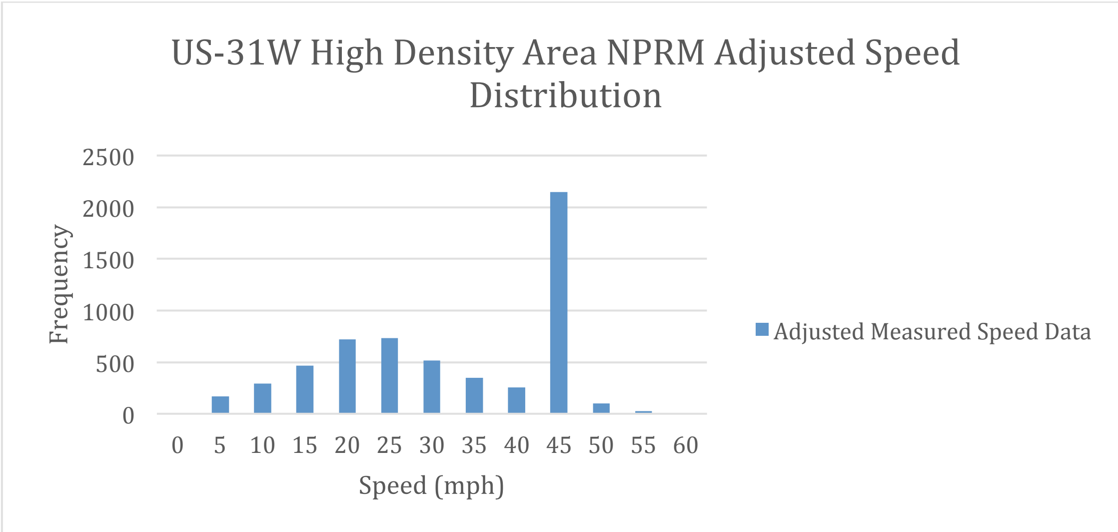


Figure 16: US-31W High Density Weekday Adjusted Speed Distribution

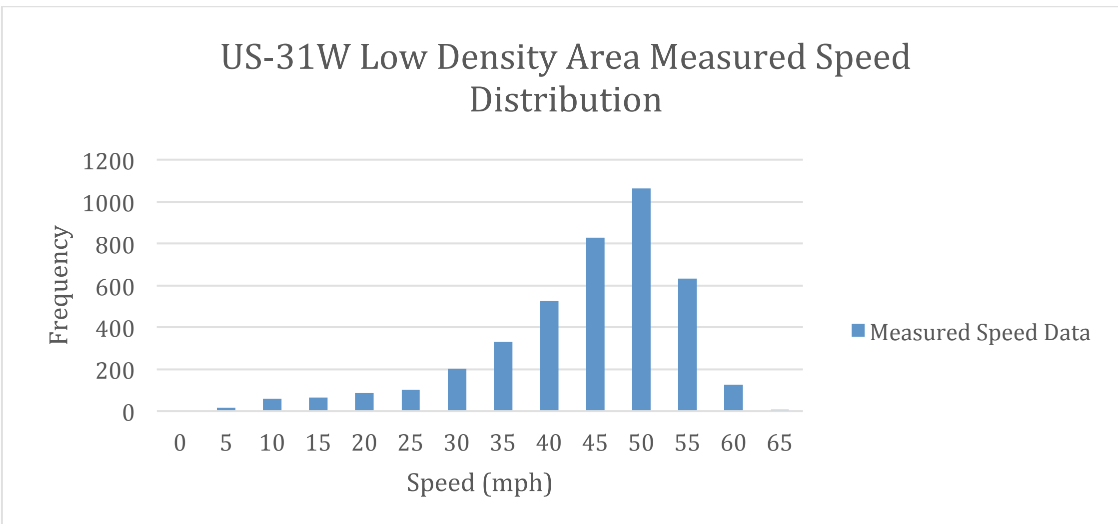


Figure 17: US-31W Low Density Weekday Speed Distribution

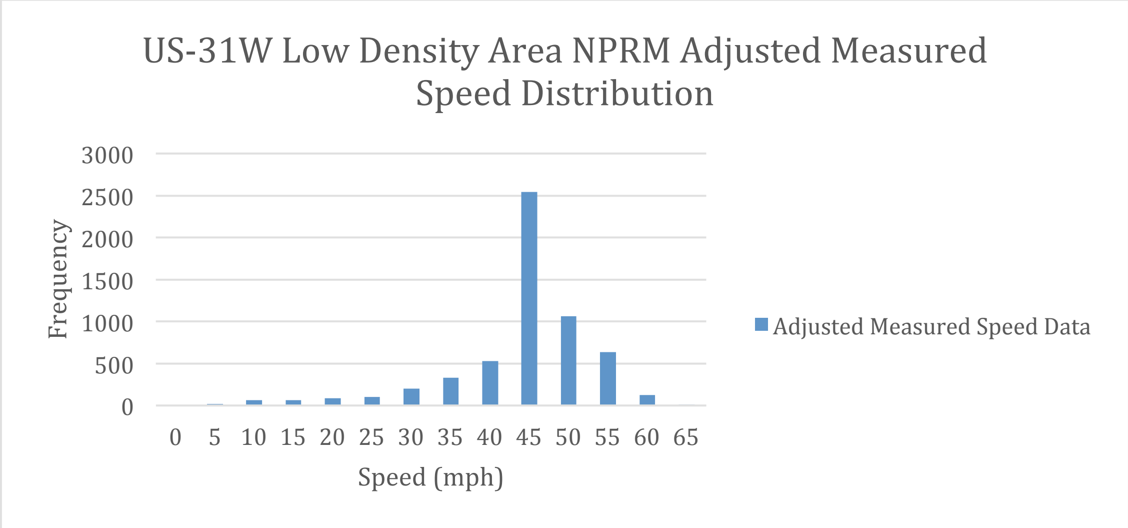


Figure 18: US-31W Low Density Adjusted Speed Distribution

In Figure 13 the measured speeds on the US-231 corridor are clustered below the local speed limit of 45 mph with most speeds occurring in the 25-35 mph range. In Figure 14 after the adjustment using the *NPRM* methodology the distribution is narrowed toward the speed limit. In the case of this network the number of speed records that are altered by the replacement methodology greatly outnumber the total number of readings that contained measured speed records on the network.

As we can see in Figure 15 the measured data in the more urban section of US-31W has many speed records most of which are clustered before the speed limit of 45 mph. When the data is adjusted using the *NPRM* methodology in Figure 16 the speeds are now clustered around the speed limit. This does not change the shape of the distribution overall but does narrow the data toward the speed limit due to the large number of null or 0 speed readings.

In the case of the more rural segment of US-31W as seen in Figure 17 & Figure 18 when vehicles are no longer inhibited by traffic signals more travelers travel along the facility at speeds more similar to the speed limit. We can see that when the speeds are adjusted based on the *NPRM* methodology however that the majority of speed records once again are narrowed toward the speed limit. This is again due to the large number of speed records that are null or equal to 0.

Based on the above tests, using the *NPRM* methodology for data adjustment would significantly decrease the variability of speed records on all facilities presented herein. As such caution should be taken by analysts when using this methodology to adjust measured speed data. Further tests are performed herein relating to the total amount of data that may be replaced using the *NPRM* methodology while still not appreciably changing the outcome of performance measure calculations.

2.6.3 Comparison of Accepted and Proposed Performance Measures

After the examination of the speed distributions the next step was to calculate performance measures at each of the three locations. The process began with the calculation of the travel time index. In order to find the typical travel time index across each 15-minute interval of the day the speed records were first aggregated to a typical weekday level (typical Monday-Thursday and Typical Friday in the US-231 case). These typical weekday speeds were then used in conjunction with the speed limit (serving as the free-flow speed herein) to determine the measured travel time and free-flow travel time needed when calculating TTI. Equation 7 was used to determine TTI during each 15-minute period throughout the day.

$$TTI_{15} = \frac{\text{Travel Time}_{15}}{\text{Free Flow Travel Time}} \quad (7)$$

where;

TTI_{15} = 15-minute yearly aggregate travel time index for period under analysis

$Travel\ Time_{15}$ = Yearly aggregate 15-minute travel time for period under analysis

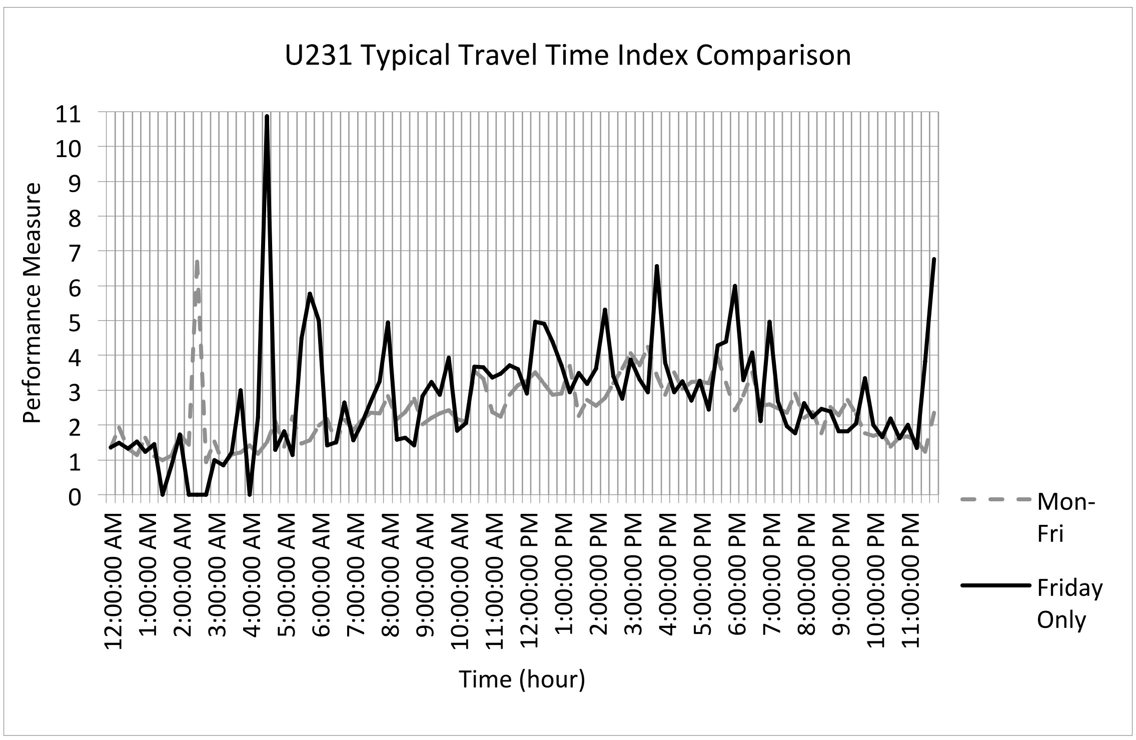


Figure 19: US-231 Travel Time Index

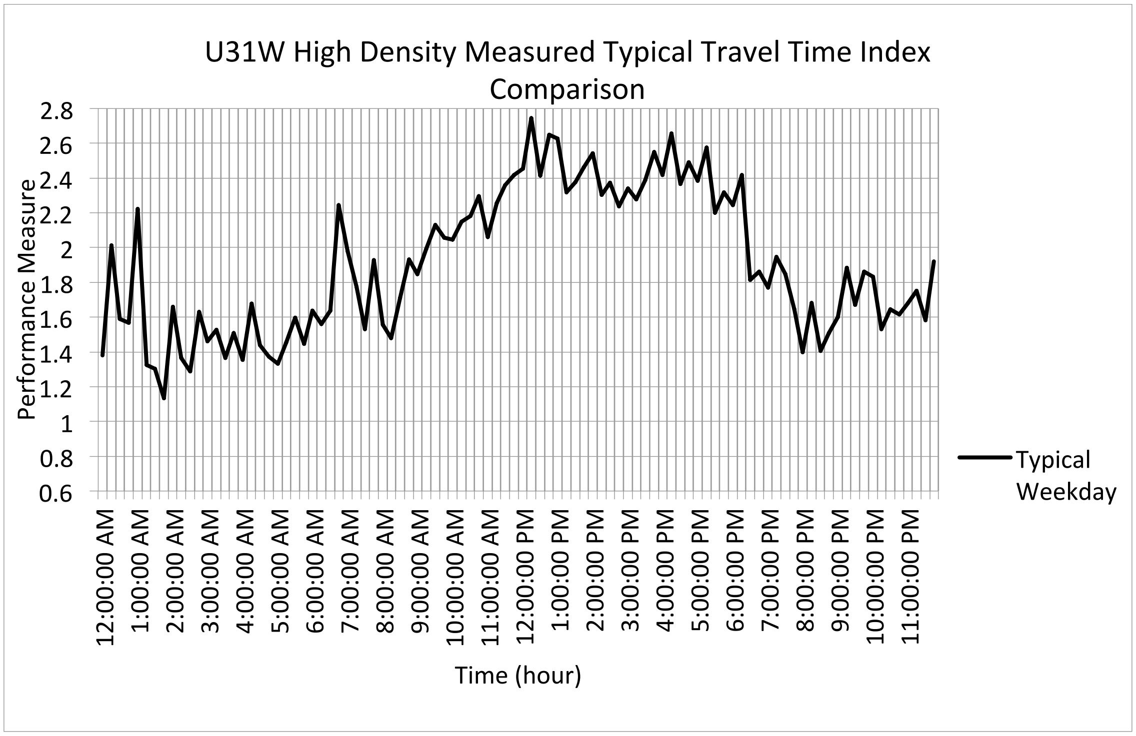


Figure 20: US-31W High Density Area Travel Time Index

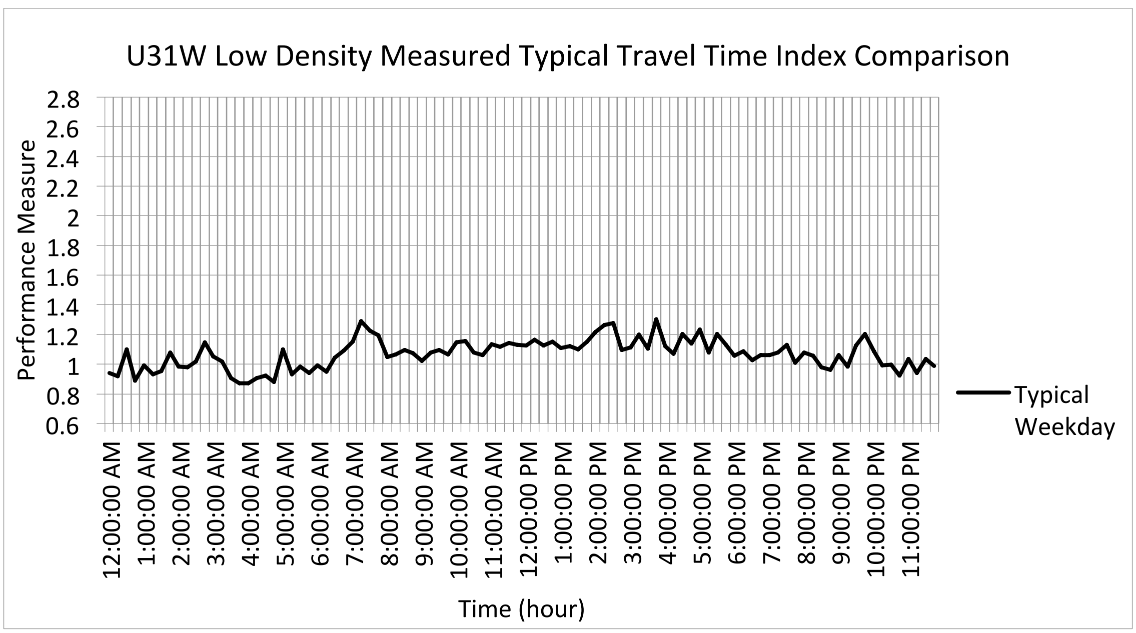


Figure 21: US-31W Low Density Area Travel Time Index

We can see in Figure 19 that Fridays on the US-231 facility have a much higher typical travel time index throughout the day than other typical weekdays. Examination of the measured speed records indicates that the periods of extremely high TTI (4:30 AM) seen above are calculated from very few measured speed records. Also of note are the 0 TTI values present in US-231 data above. These data points do not actually reflect a 0 TTI value, these values are points where no measured speed data is available for that time period. It may also be observed that both the US-231 facility and the portion of the US-31W facility with high signal density have large variations in their TTI throughout the day whereas the low-density portion of US-31W does not. This is logical as there is a strong correlation between the land use at each study site and the recorded speeds observed there. Both the US-231 network and high-density portion of US-31W are surrounded by highly commercialized areas containing many restaurants (US-231) and retail shopping locations (US-231 and US-31W). (Refer to Figure 2, Figure 3, and Figure 5 for aerial photos of the US-231 and high density US-31W sites). This type of land use leads to greater variation in volume throughout the day and greater volume in general as compared to the more rural surrounding area present near the low density segment of the US-31W site seen in Figure 6.

Based on the LOS boundary conditions detailed in section 2.6.1 the US-231 facility operates at a LOS D during the AM peak and LOS E during the PM peak periods. This makes sense as the PM peak LOS as the US-231 site is expected to be lower than the AM peak as volumes increase during this period due to the influx of travelers frequenting the many restaurants near the facility. The low LOS during the AM peak period can be attributed to normal commuter congestion on the facility.

The high-density portion of US-31W ranges from LOS C during the AM peak period to LOS D during the PM peak. It is important to note however that the primary peak period for this segment of US-31W occurs during the noon hour. Here the facility operates at LOS E for the entirety of the time period. This is important to note as the proposed rulemaking procedure does not call for the PHTTR to be calculated for this hour. This means that areas that experience a peak period during the noon hours will not have this period accounted for by the PHTTR metric. As such inclusion of a noon peak period from 11:00AM to 2:00PM should be considered for future PHTTR research. The low-density portion of the same facility ranges from LOS A during the off-peak periods to LOS B during the AM and PM peak. These LOS estimates are logical based on the correlation presented above relating land use and recorded speed at each location.

With the TTI determined for each facility the PHTTR was then found for comparison. Using the methodology explained in the *NPRM* the highest single hour travel time for each hour of the 6-9AM and 4-7PM peak periods was found. This travel time was used as the peak hour travel time in the PHTTR equation. For the desired peak period travel time used in the equation, percent of free-flow speed values were adopted from a study by Turner *(11),* who categorized performance measure target speed values based on intersection density. These values are summarized in Table 5. These speed-density relationships were adopted for use when determining the desired peak period travel time. For the purposes of this research the speed limit on the facility was substituted in place of the prevailing light traffic speed.

Table 5: Performance Measure Target Speed Values

Intersection Density (Intersections per mile)	Target Value = Percent of Prevailing Light Traffic Speed
<2	100
2 to 4	90
4 to 8	85
More than 8	75

The desired travel speed and travel time based on the speed-density relationship is given in Table 6.

Table 6: Desired Peak Period Speed and Travel Time

Segment	FFS	Length (miles)	Desired Percent of FFS	Desired Speed	Desired Travel Time (sec)
High Density	45	0.423	75	33.75	45.12
Low Density	55	1.83	100	55	119.78
US-231	45	1.243	85	38.25	116.99

Once the desired travel time on each facility was found the PHTTR could then be calculated. Table 7 gives the PHTTR values for each facility at the proper level of aggregation. Note that a facility is considered to be meeting expectations when the value of its PHTTR is below 1.50. Recall that the PHTTR is to be calculated for the AM (6:00AM-9:00AM) and PM (4:00PM-7:00PM) periods separately.

Table 7: PHTTR Values

PHTTR	US-231		US-31W High Density		US-31W Low Density	
	AM Peak	*PM Peak*	*AM Peak*	*PM Peak*	*AM Peak*	*PM Peak*
Monday-Friday	-	-	2.06	4.64	1.42	1.43
Monday-Thursday	1.63	3.19	-	-	-	-
Friday	1.56	4.00	-	-	-	-

Table 8: PHTTR Based LOS Measures

PHTTR	US-231		US-31W High Density		US-31W Low Density	
	AM Peak	*PM Peak*	*AM Peak*	*PM Peak*	*AM Peak*	*PM Peak*
Monday-Friday	-		E	F	B	B
Monday-Thursday	C	F	-	-	-	-
Friday	C	F	-	-	-	-

Based on the information contained in Table 7 US-231 Scottsville road does not meet the proposed expectations during either peak hour in the typical week. Based on the previously defined LOS boundary values the facility operates at LOS C during the AM peak period and LOS F during the PM peak period. While the PM peak period estimate is consistent with the TTI based LOS estimate presented above the AM peak period LOS indicates a less congested facility. It should also be noted that the PM peak LOS metrics agree when the traffic on the facility reaches breakdown conditions (LOS F). As there are no sub-levels within the LOS F measure it is not possible to determine if the two metrics truly indicate the same level of traffic breakdown or if the agreement between metrics is simply due to the PHTTR and TTI increasing above the defined LOS F threshold.

The high density portion of US-31W operates at LOS E during the AM peak period and LOS F during the PM peak period per the PHTTR. It should be noted that neither the AM or PM peak period LOS estimate is consistent with the TTI based LOS metrics. Both the AM peak and the PM peak fall two categorical LOS measures based on the PHTTR definition.

The low density portion of US-31W operates at LOS B during the AM and LOS A during the PM peak period. This again shows a drop in one categorical value of LOS as the LOS falls from A (based on TTI data) to B (based on PHTTR data).

It is important to note that while the TTI and PHTTR methods of LOS calculation generally agree in cases on the more rural, low density segment of US-31W they do not produce the same LOS when applied to the two more urbanized arterial segments. A small drop in the estimated LOS from the TTI based method to the PHTTR based method is expected (due to the PHTTR based method using a lower reference speed). Furthermore, the high density segment of US-31W has the lowest reference speed used in this study and similarly shows the largest drop is LOS across all facilities. It is noted that the lower the desired speed used in the PHTTR calculation of desired travel time, the lower the metric will be. Consequently, it this metric could be manipulated to produce better ratios using a lower desired speed than that actually appropriate for a facility under study.

In addition to the TTI and PHTTR the level of travel time reliability and planning time index were also calculated for all networks. Because the planning time index represents a measure of the extra travel time needed to arrive on time, the level of travel time reliability should show a marked decrease when the PTI becomes less stable. This is because when the PTI fluctuates travelers must add differing amounts of extra travel time to their trip to arrive on time at a destination. The measured PTI and level of travel time reliability (LOTTR) are given in Figure 22-Figure 27. It should be noted that the threshold for level of travel time reliability is 1.50 with facilities operating under this value at all times considered to be reliable.

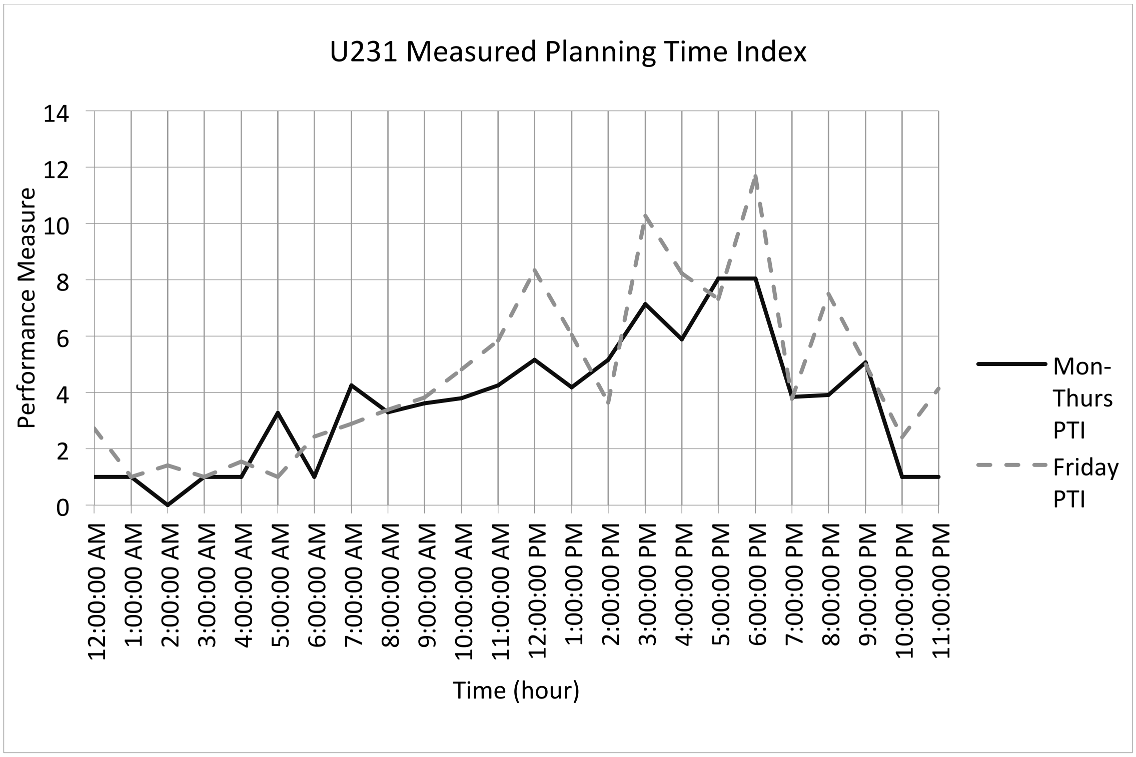


Figure 22: US-231 Measured Planning Time Index Data

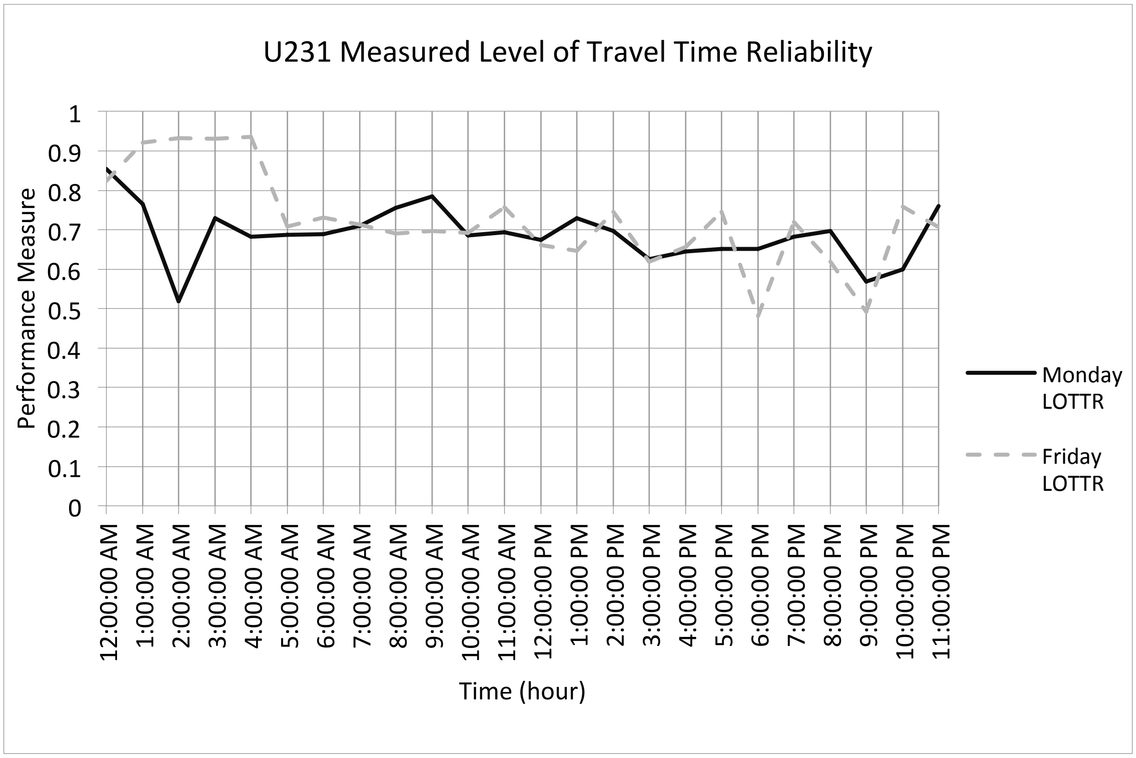


Figure 23: US-231 Measured Level of Travel Time Reliability Data

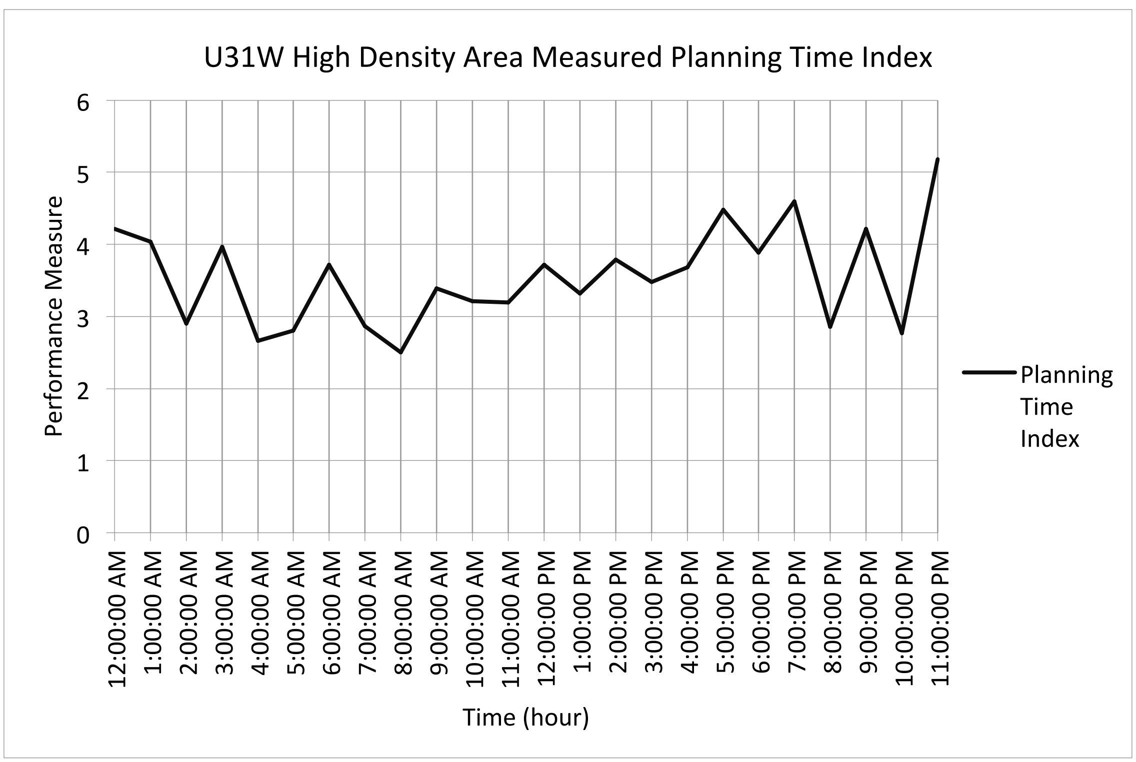


Figure 24: US-31W High Density Planning Time Index Measured Data

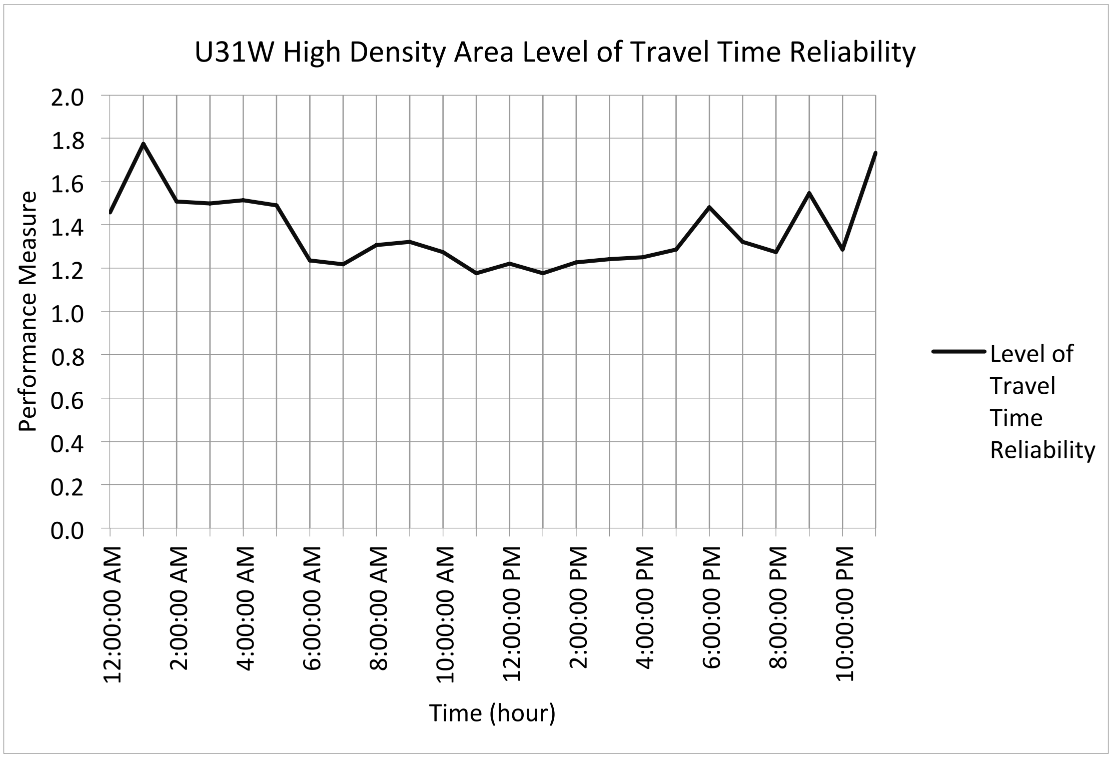


Figure 25: US-31W High Density Level of Travel Time Reliability Measured Data

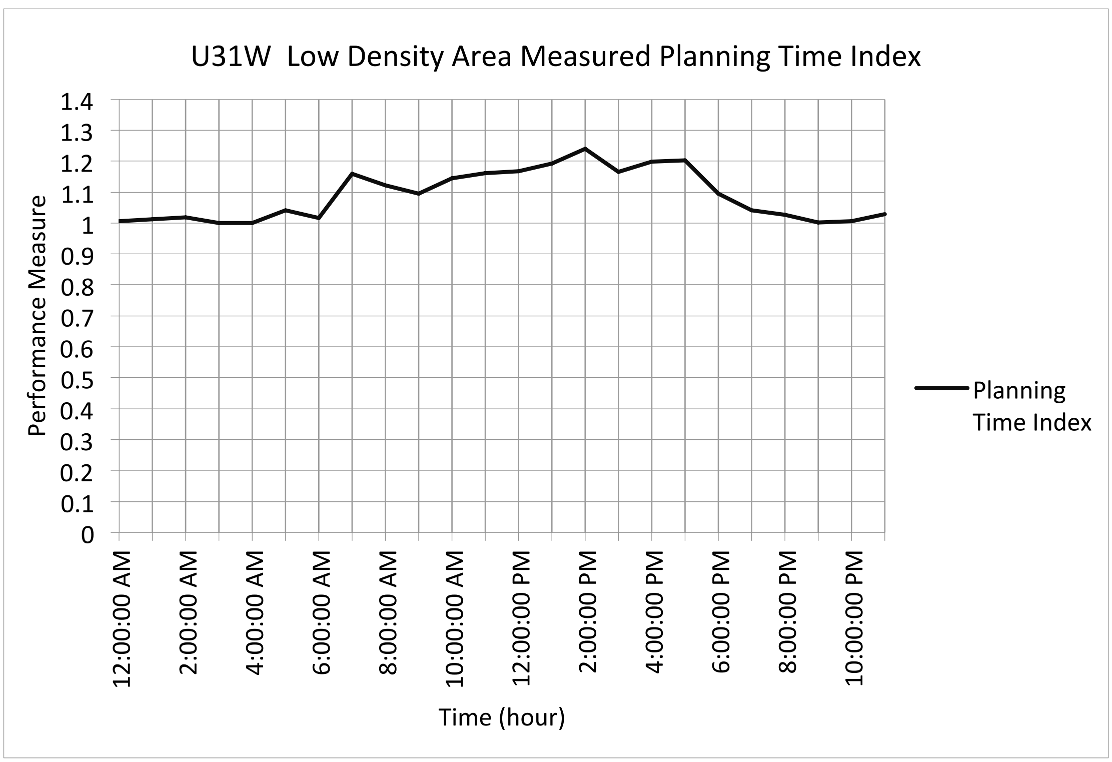


Figure 26: Low Density Measured Planning Time Index Data

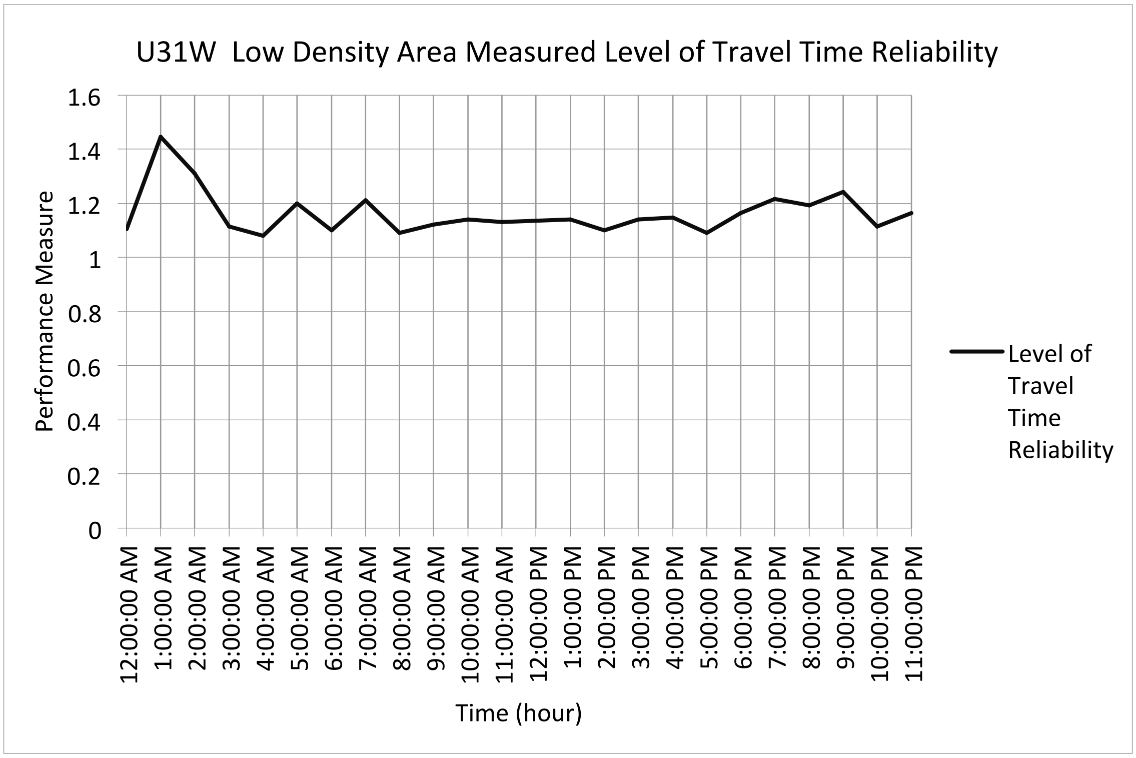


Figure 27: Low Density Measured Level of Travel Time Reliability Data

Based on both the PTI and LOTTR data presented above only the low density area of the US-31W network can be considered reliable. The high density segment of US-31W presents a LOTTR that indicates a reliable facility during all periods, remaining relatively stable until the 5:00PM hour when a slight increase is noted. This is in contrast to the PTI that shows large periods of extra travel time throughout the entire day. The high density portion of the network also shows a lower level of travel time reliability during the late night hours. This is counterintuitive as the late night hours should contain less volume and thus less congestion than the day time hours. Examination of the measured data shows that this decrease in the level of travel time reliability is due to an abnormally low 20th percentile speed during the 11:00 PM hour as well as a high 50th percentile speed during this time period. Figure 25 below shows this as the 50th and 20th percentile speeds converge during the midday hours before diverging greatly during the 11:00 PM hour. This large difference between the two speeds explains the large drop in travel time reliability on this network during these hours. It should also be noted from Figure 10 above that the number of speed records during the late night hours are much fewer than those during the rest of the day. As such caution must be used when drawing any conclusions based on data records from the late night hours in this case.

Furthermore, the 5th percentile speed falls significantly during the hours between the AM peak (6:00AM-9:00AM) and PM peak (4:00PM -7:00PM). This explains the climb we see in PTI in Figure 24. It should be noted however that when the number of speed records was examined for the US-31W network in Figure 11 fewer than 20 records were present for any hour outside of this period. This means that the percentile speeds calculated outside of the period between the AM and PM peak periods may not truly reflect the population percentile speeds during those hours. Consequently, the low PTI produced by these 5th percentile speeds during the early AM and late night hours may not accurately reflect conditions on the facility.

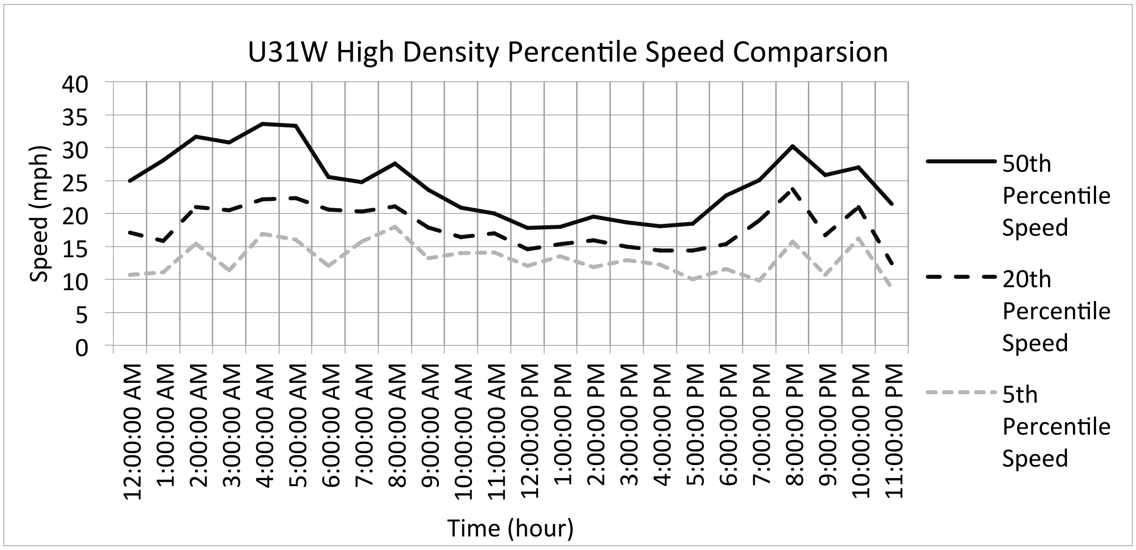


Figure 28: Comparison of Measured Percentile Speeds on US-31W High Density Segment

The PTI and LOTTR produce differing views of the US-231 facility. Based on the LOTTR the facility operates reliably during all days of the week. The PTI shows the facility operating unreliably during all days with Friday being the worst day on the facility. This confirms information obtained by local sources. This difference in values of travel time between the two metrics can be explained by the similarity of the 50th, and 20th percentile speeds on this network Figure 28 and Figure 29 below show the measured speed percentiles on the US-231 network. As we can see in the figures in most cases the difference between the three percentile speeds remains relatively constant. The greatest exceptions to this are the late night hours during Friday.

It should also be noted from Figure 28-Figure 30 that the difference between the 50th and 20th percentile speeds shows little variation throughout the day. This accounts for the low variation seen in the LOTTR metric as this performance measure is based on the ratio of these two speeds. Since both speeds rise or fall at nearly the same rate throughout the day, the metric changes very little. This is in contrast to the PTI. Because the PTI is referenced to a fix speed (the speed limit in this case) the variability of the metric is directly related to the variability of the 5th percentile speed. This explains the differing values of travel time reliability explained by the two metrics while also highlighting a limitation of the LOTTR metric. As it is currently calculated the LOTTR reports a planning level estimate of the travel time reliability of the facility. The PTI in contrast presents the average traveler's experience on the facility. As such caution must be used when comparing the output of the two metrics. The LOTTR may be used for the facilities under study herein, to generate high level planning estimates of travel time reliability. The PTI may be best used to determine problem locations for future reliability analysis, as seen from the average traveler's perspective.

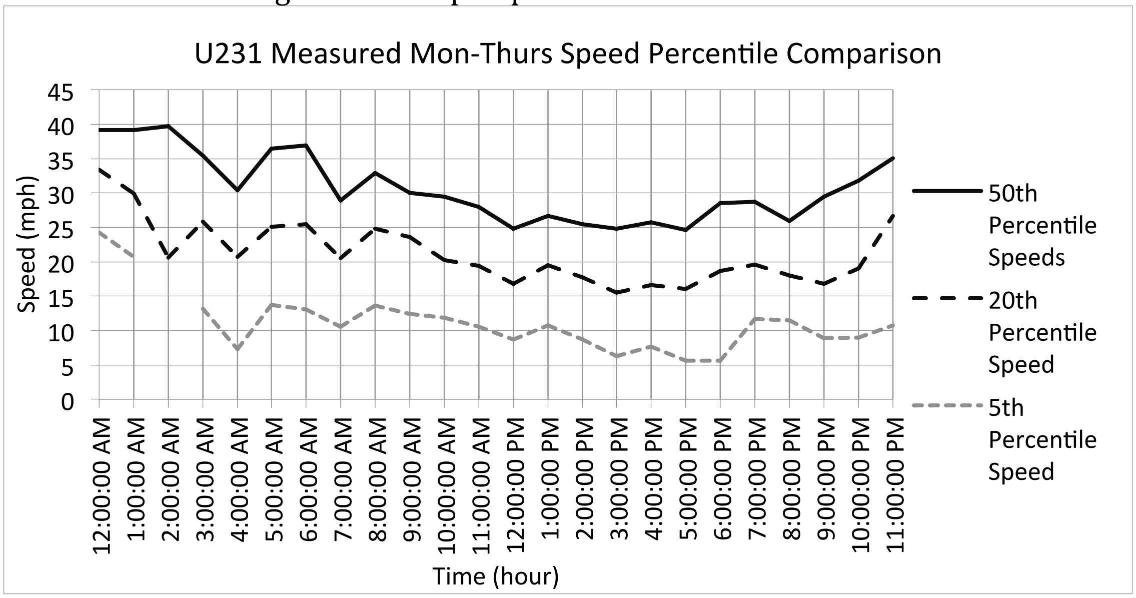


Figure 29: Mon-Thurs Measured Speed Percentile Comparison

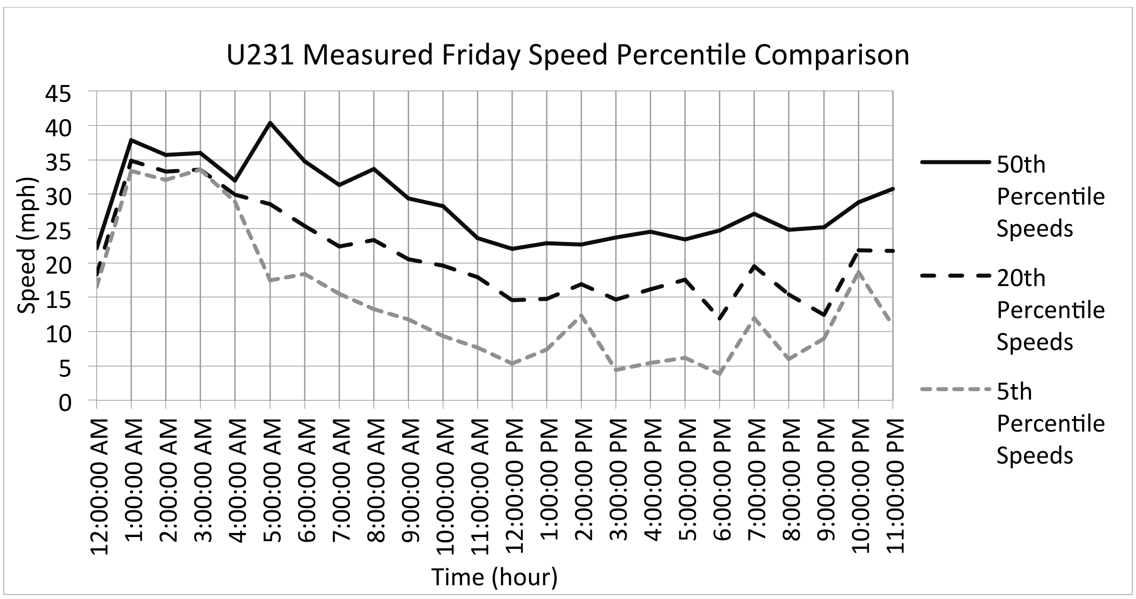


Figure 30: US-231 Measured Friday Percentile Speed Comparison

2.6.4 Observations Drawn from Performance Measure Tests

Several conclusions can be drawn from the comparison of the current and proposed performance measures. First and foremost is that quantifying arterial travel time reliability is challenging. There are many metrics available for use and each may indicate a different picture of reliability on a facility. In this thesis three arterial networks were examined using the LOTTR, PHTTR, TTI, and PTI performance measures. It should be noted that on two of the networks used the proposed measures and TTI and PTI do not compare well. The proposed metrics indicate a more reliability facility than the TTI and PTI do in the case of the networks herein examined. As the proposed metrics do not give a consistent picture of facility reliability as the TTI and PTI, future research is needed to examine the validity of using the proposed performance measures for arterial travel time reliability estimation.

The time period for which the proposed PHTTR metric is to be calculated was also shown to be an issue for one network examined herein. In the case of the US-31W high density segment the true peak period occurs during the noon hour and is not accounted for by the proposed PHTTR calculation methodology.

Furthermore, no matter the metric chosen a reference travel time or travel speed is always needed. There are many accepted methods of determining this reference value (see section 2.5 above) but there is not currently a generalized method that works well for all arterial sites. The choice of this speed is as important as the choice of travel time reliability metric as an improper reference speed can cause over or under estimates of reliability.

CHAPTER 3 USING PERFORMANCE MEASURES TO SUPPORT PROJECT DECISION MAKING

Despite the use of performance measures in measuring current conditions on a facility, there is currently no standardized methodology for evaluating performance measures on a subject facility after project implementation. This is due to the need for measured speed or travel time data when calculating reliability or congestion performance measures. Measured data for future projects by definitions is unavailable. In order to calculate performance measures for new conditions after project implementation, estimates of future speed and travel time data are needed. This estimation is now made possible through the use of macro level roadway simulation tools. One such tool, the *Urban Streets Reliability Module* will be explained in detail herein.

3.1 Urban Streets Reliability Module

The *Urban Streets Reliability Module* (USR) was created by McTrans based at the University of Florida. This tool serves as an add-on module to the *HCS 2010* software suite. This tool uses the *HCS 2010*: Chapter 17 urban streets and Chapter 18: signalized intersection methodology to estimate future conditions on a facility *(13)*. Estimates of travel speed and travel time are presented based on user input to the tool. As the USR tool uses an *HCS* 2010 network as a basis, many of the same inputs are shared between *HCS 2010* and the USR tool. These inputs include the following:

- Facility Geometry
- Signal Timing Plans for the Period under Study
- Demand Adjustment Factors
- Yearly Weather Data
- Measured Volume Counts on the Subject Facility
- Traffic Incident Counts on the Subject Facility during the Analysis Year

Facility geometry includes such items as lane width and curb presence. Signal timing plans are used by the tool to determine the amount of green time allocated to each movement at a signalized intersection on the facility (and thus the capacity of each movement). Demand adjustment factors corresponding to the percentage of AADT that occurs during a given time period and are used to adjust the measured volume data to create an estimated AADT. Yearly weather data may be obtained using a database contained within the tool of NCDC cities. There are currently over 100 NCDC locations contained within the database.

Using the data items presented above the USR tool is able to estimate the current and future years data based on current measured facility data. Outputs from the tool are provided in the form of hourly or 15-minute aggregate travel time or travel speeds values at the corridor wide level.

It should be noted that the USR does not currently have the ability to model actuated signalized intersections. As such when modeling corridors containing intersection coordination the analyst is restricted to modeling those time periods that fall under one of the coordination timing plans present on the facility. A further limitation of the tool is the inability to model facilities which experience queue spillback (when queue from a downstream intersection extends into the upstream intersection). In cases where spillback occurs the USR may overestimate volume on a facility.

When properly calibrated the USR tool provides the analyst with a high planning level estimated of facility performance measures. It should be noted that the USR tool is a macro level planning tool and is best used to produce average conditions on a facility rather than micro level performance estimates.

In order to test the capability of this tool to estimate conditions on a facility tests were performed using measured data from each of the sites noted above. Calibration of the USR model to current facility conditions was completed followed by subsequent tests of the USR's ability to estimate future conditions and assist in project decision-making.

3.2 USR Network Calibration

As stated above each network to be evaluated using the USR must first be created in *HCS 2010* streets. What follows is the process undertaken to calibrate each network to facility specific conditions so that each may provide the most accurate data possible.

3.2.1 US-231 Network

The initial US-231 network was created as part of the SHRP2: Project L08 initiative to test arterial travel time reliability tools on networks throughout the state of Kentucky. Measured volume data for the US-231 facility was provided by CDM Smith Engineering as part of a previous access management study conducted on the facility *(2).*

Initial tests of the USR found that spillback issues on side street locations significantly affected the analysis. To combat this issue, the side street storage length was increased so that in the model vehicles were able to accumulate from the stop bar at the intersection of the side street and US-231 to the nearest upstream intersection found on the side street. This meant that several unsignalized access points along the various side streets may be blocked by queue build-up from the intersection. As these side street locations were not the primary focus of the model, but rather their intersection with the main line of US-231, this was considered acceptable.

Demand adjustment factors pertaining to the day-of-week and month-of-year were obtained via the Kentucky Transportation Cabinet. Hour-of-day demand adjustment factors were created based on the 15-minute volume counts conducted as part of the previous study by CDM Smith Engineering.

As mentioned previously the US-231 facility contains many unsignalized access points. The largest two access points on the facility (Pedigo Way and the Greenwood Mall Entrance) were shown to cause variations in the estimated volume on the facility when they were excluded from the model. Review of existing *HCS 2010* documentation revealed that large access points such as these should be coded into the network separately with their location referenced in ft from the upstream signalized intersection.

Signal timing data for the intersections contained within the US-231 network was provided by the Kentucky Transportation Cabinet. This information was for the year 2013 to ensure that the proper signal timing plan would be used to calibrate the model to the same year as the measured data. It should be noted that 4 separate timing plans take effect on the facility throughout the day. As such each time the timing plan changed a new iteration of *HCS 2010* streets and thus a new iteration of the USR tool was needed. This presented an issue wherein the final queue from the previous signal timing plan was not carried over as the initial queue in the next iteration of the model. This was shown to affect the subsequent 15-minute period after a timing plan change the most heavily with other subsequent periods seeing only minor effects.

As no National Climatic Data Center weather station is present in Bowling Green, the nearby facility present in Nashville, TN served as a surrogate weather data location. The proximity of Nashville to Bowling Green (66 miles) is close enough that weather between the two sites can be assumed to be similar.

3.2.2 US-31W Networks

In the case of US-31W creating a new network was not necessary as a previous study by Palmer Engineering utilized *HCS 2010* for the evaluation of US-31W from Elizabethtown to Radcliffe, Kentucky. This network contained 20 signalized intersections. Field measured data showed the saturation flow rate to be approximately 1750 vph on the facility. Two segments of this network were extracted for use with the USR.

As the study conducted by Palmer Engineering contained measured data only for the PM peak hours 4:00PM-5:30PM (16:00-17:30) volume counts on the facility were estimated during the rest of the 24-hr day. This process used the day-of-week and hour-of-day demand adjustment factors to calculate volumes during each hour. This is shown in equation 8.

$$V_{6:00} = \frac{D_{6:00}}{D_{4:00}} \times V_{4:00} \qquad (8)$$

where;

$V_{6:00}$ = Volume at 6:00 PM

$D_{4:00}$ = Demand adjustment factor corresponding to 4:00 PM

$D_{6:00}$ = Demand adjustment factor corresponding to 6:00 PM

$V_{4:00}$ = Measured volume at 4:00 PM

As there is currently no NCDC weather station in either Elizabethtown or Radcliffe, KY the weather station in Louisville, KY was adopted for use in this model. The proximity of Louisville to the Elizabethtown area limits the difference in weather conditions that would possibly be experienced at both sites.

Demand adjustment factors were obtained from the *Kentucky Traffic Forecasting Report 2008* for use with both networks. It should be noted that these factors represent an aggregation of all roadways of similar functional class within the state and are not to be used in place of facility specific data. Furthermore, as the traffic forecasting report contained no demand adjustment factors for weekend days the default values (representing an aggregated average of weekend days across L08 study facilities) present in the USR were used.

As the high density portion of the facility operates under signalized intersection coordination only during the hours of 6:00AM to 8:00PM only these hours could be modeled due to the limitations of the USR tool. As such the low density segment of the facility was also modeled under these time periods only to allow for comparison.

The USR simulation of the US-31W networks was completed for the 2012 year to allow for a comparison to the baseline measured data. This comparison serves as a reasonableness check to determine the model's accuracy before proceeding to estimation of future data.

3.2.3 Comparison of Estimated and Measured Performance Measures

Before proceeding to future project evaluations using the USR models previously explained a reasonableness check was conducted. This involved comparison of the USR tool estimated performance measures to those calculated using the measured HERE data. This comparison would serve to establish what trends occur in the model data and to determine if the inconsistency between the currently accepted and proposed performance measures can be eliminated when a complete dataset with no null or missing values is used. This process began with the comparison of the estimated and measured speed distributions on each facility. Figure 31-Figure 33 compared the measured speed distributions the estimated speed distributions have the same general shape but are more skewed toward the central speed value of the measured distributions. Furthermore, the number of speed records in the estimated data is far larger than that of the measured data as the USR generated data contains a speed record for all 15-minute periods throughout the year. The narrowed distribution seen in the following figures is a product of this increase in the number of recorded speed records as most readings, which are null or missing in the measured data, are estimated to be speed approximating the mean speed by the USR. These missing speed records are estimated at values close to the mean speed due to the L08 methodology's inability to capture the day to day variability caused by non-recurrent sources of congestion *(15)*. Caution must be used when calculating performance measures with the estimated data as the number of speeds records near the mean speed far outweigh those on the edges of the distribution. This would serve to artificially increase or decrease reliability on the facility depending on whether the mode of the speed data is higher than the measured data (in the case of US-231 seen in) or lower than the measured data.

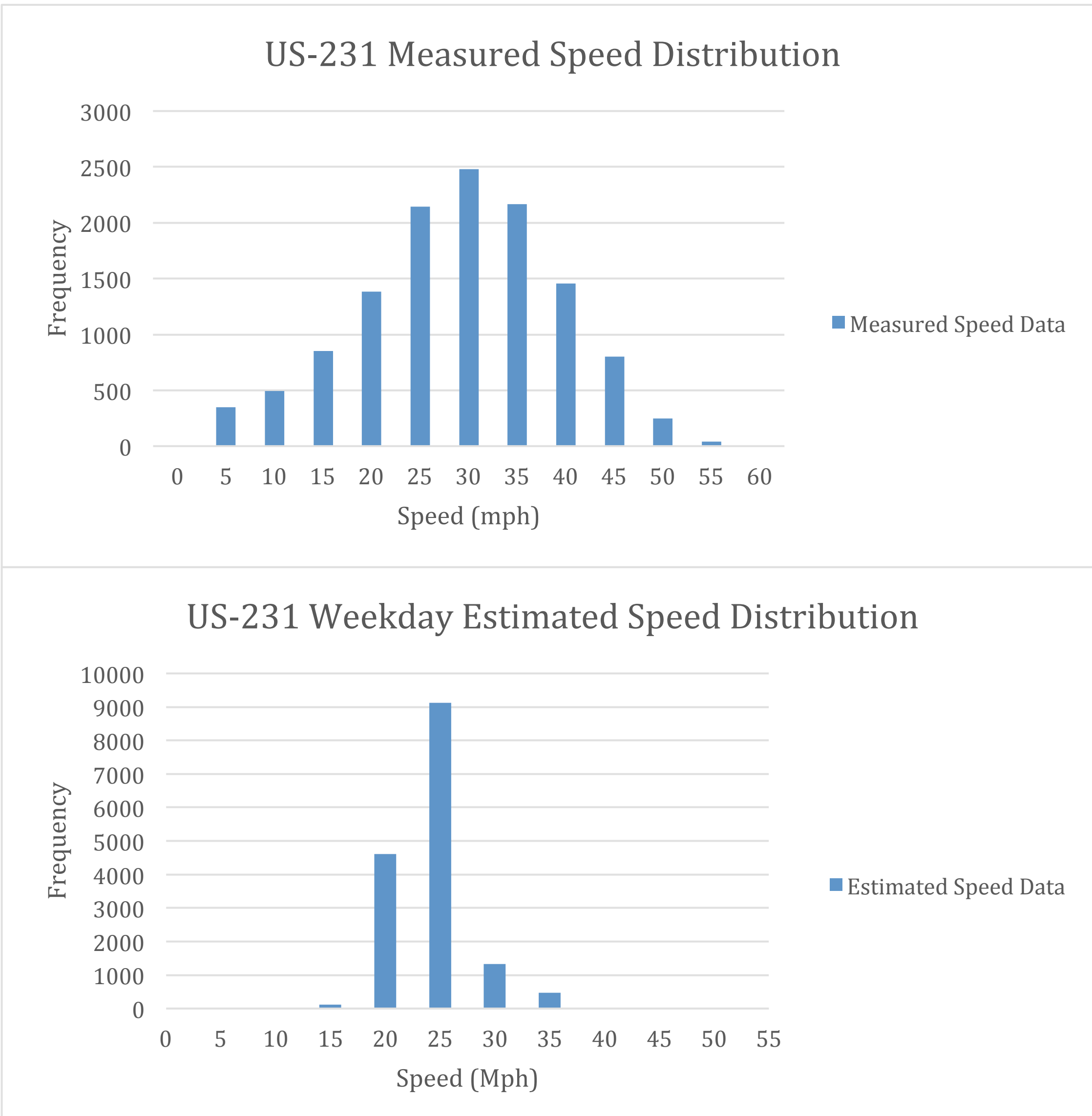
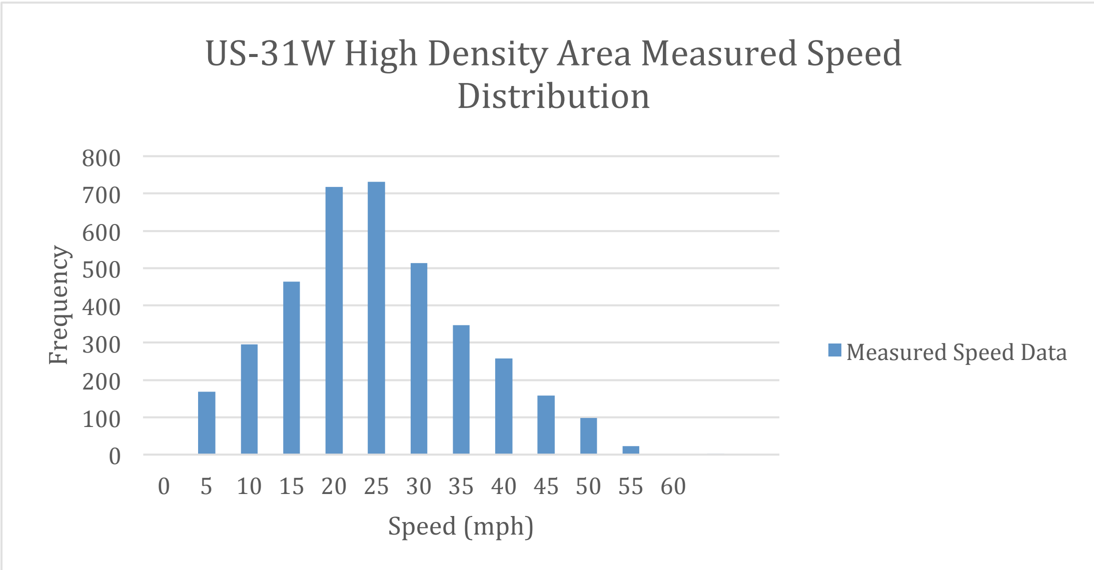


Figure 31: US-231 Estimated and Measured Speed Distribution Comparison



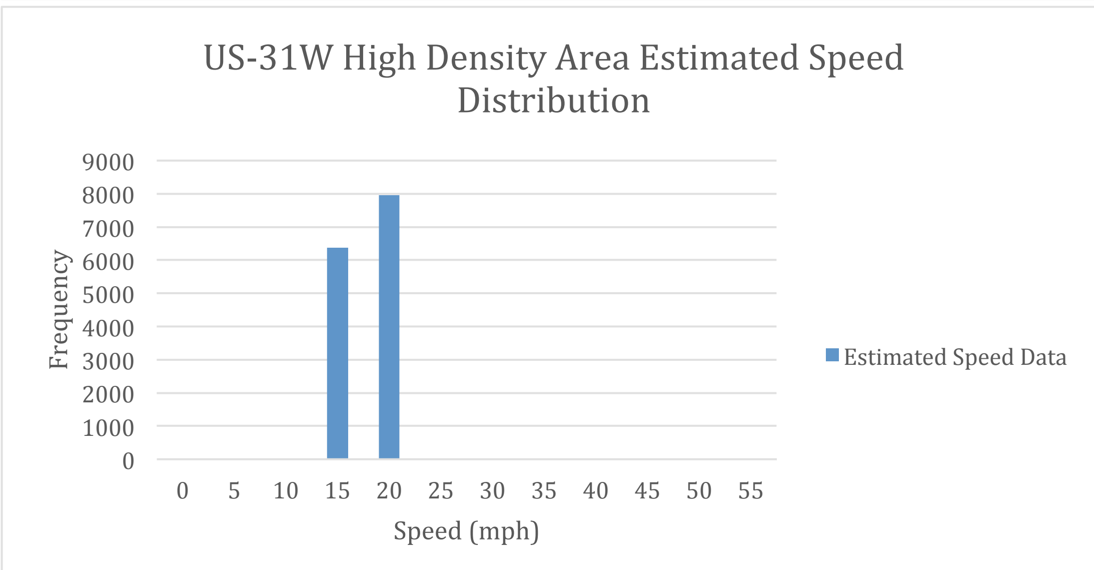
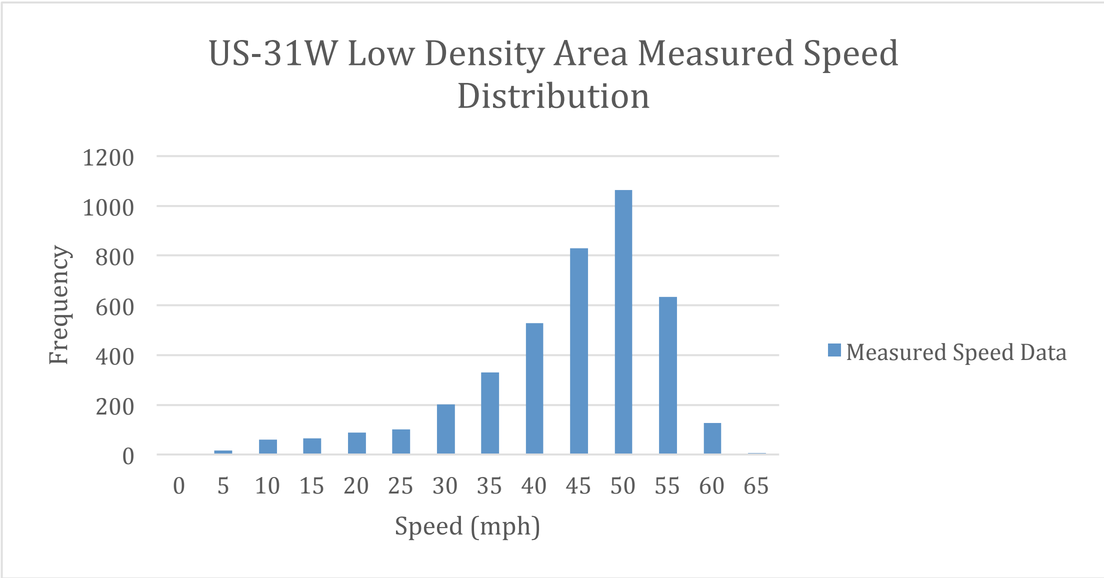


Figure 32: US-31W High Density Measured and Estimated Speed Distribution Comparison



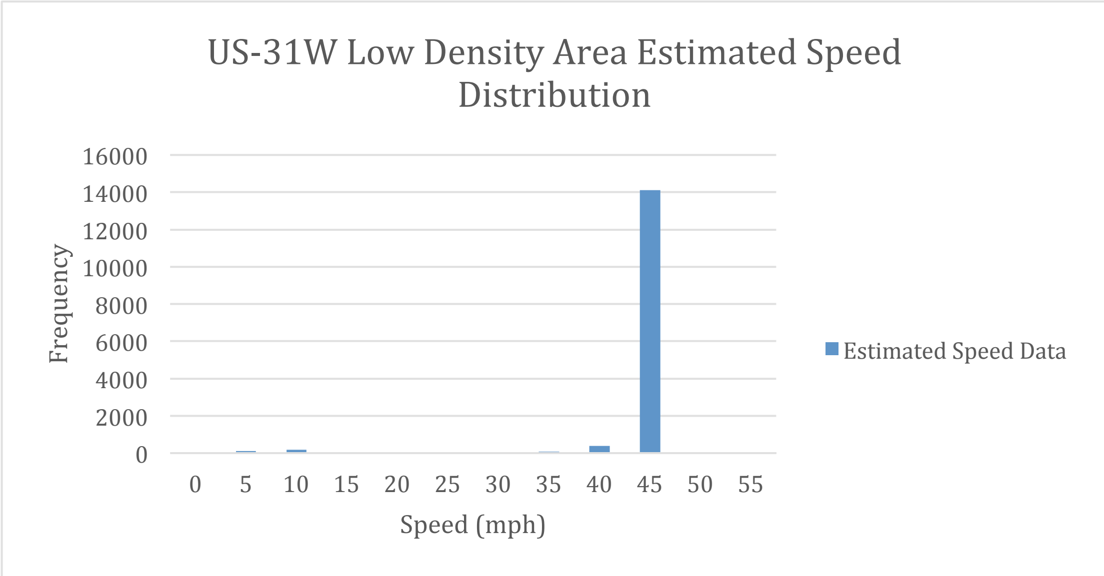


Figure 33: US-31W Low Density Measured and Estimated Speed Distribution Comparison

In addition to the comparison of the measured and estimated speed distribution, the speed profiles from the measured and estimated data were also generated for comparison. These speed profile comparisons are shown in Figure 34-Figure 37.

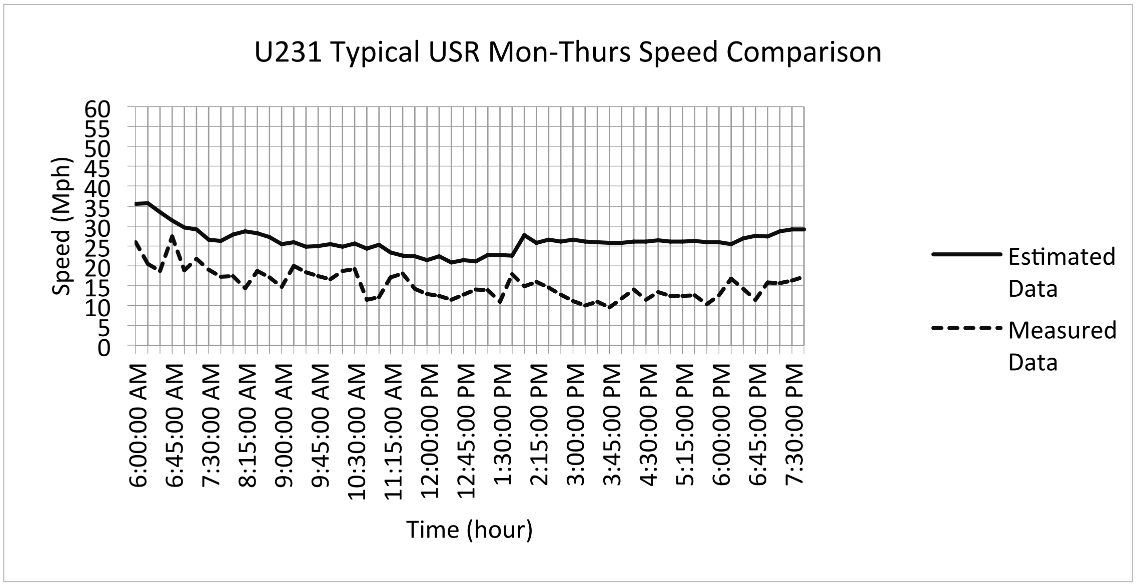


Figure 34: US-231 Mon-Thurs Estimated and Measured Speed Profiles

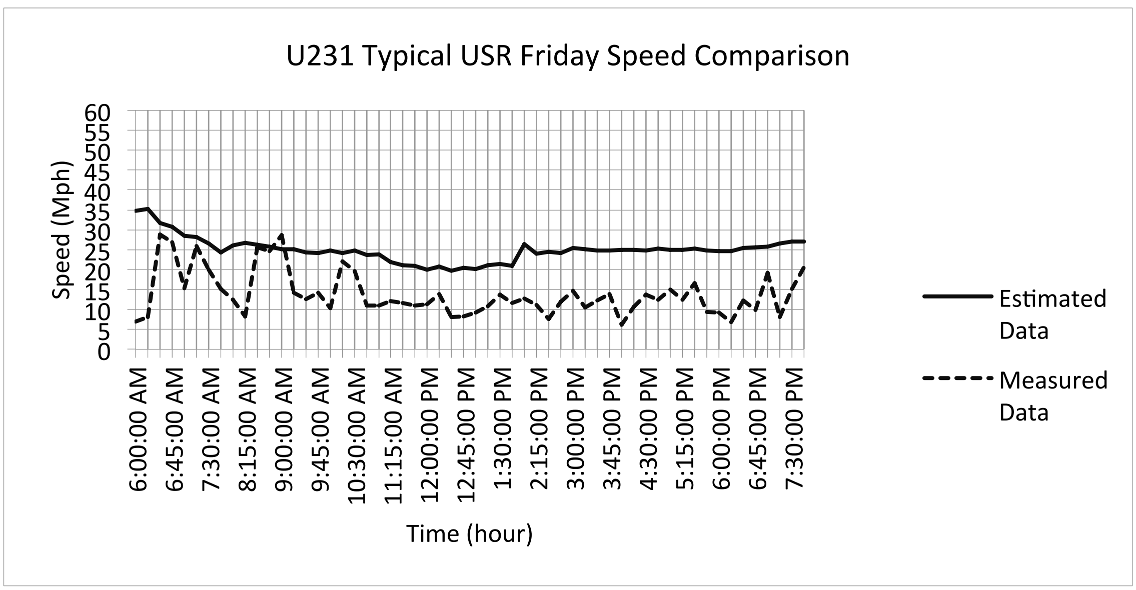


Figure 35: US-231 Friday Estimated and Measured Speed Profile

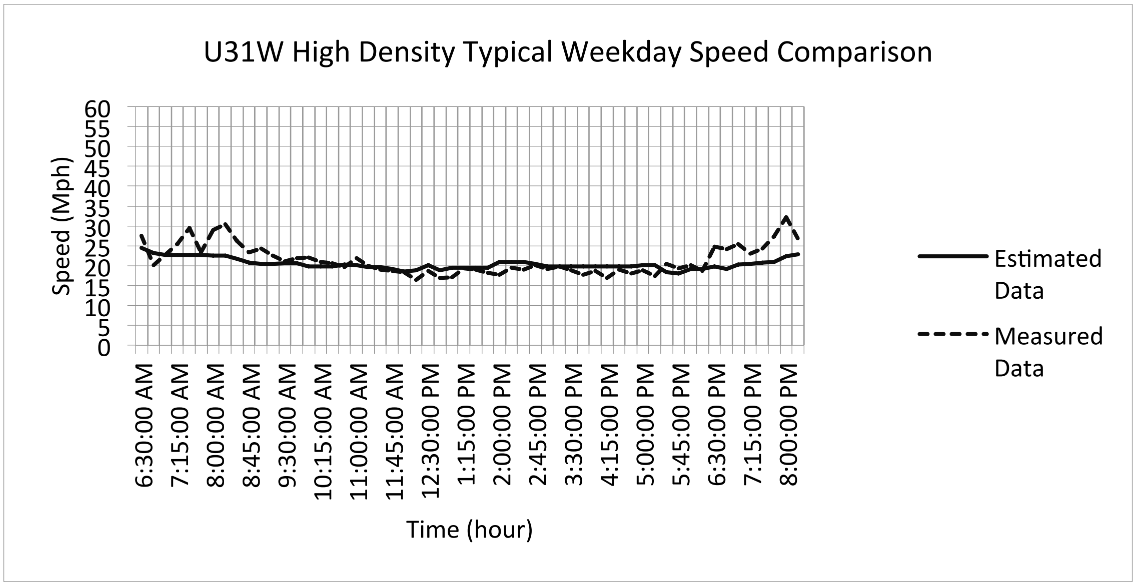


Figure 36: US-31W High Density Estimated and Measured Speed Profile

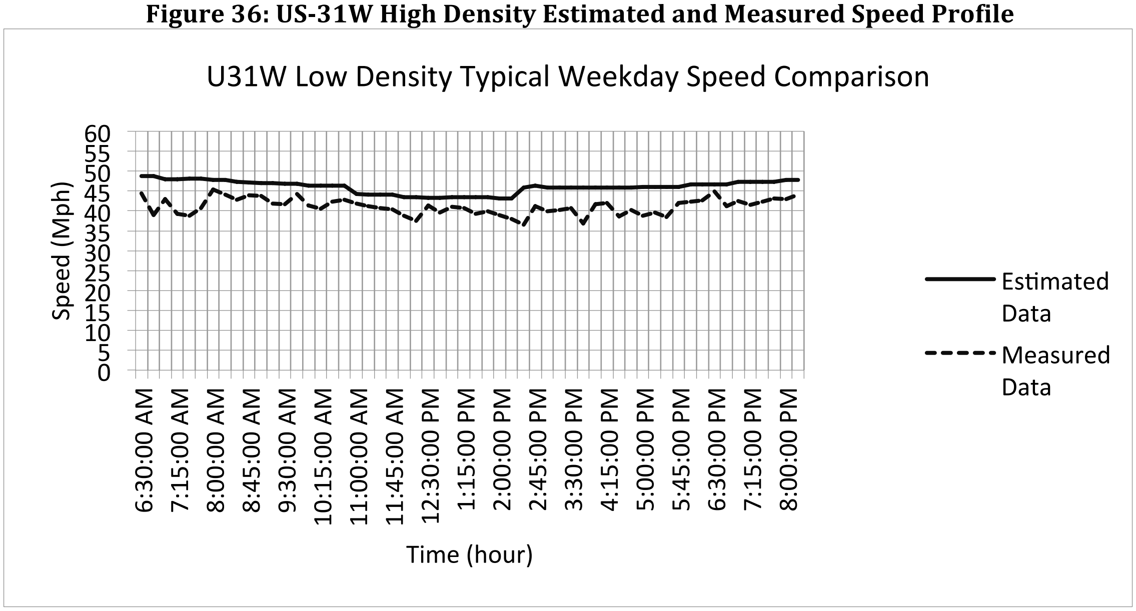


Figure 37: US-31W Low Density Estimated and Measured Speed Profile

Based on the comparisons of the measured and estimated speed profiles it can be noted that the USR produces a more average speed as compared to the measured data. This can be explained by the limitations of the USR tool (or any simulation based models) to capture the day to day variation in conditions on the facility. As such the variation noted in the measured speed data is not present in the USR estimated data. Furthermore, the USR estimated speeds are generally higher than the measured speed observed on the facility. This too can be explained by the tools inability to capture the non-recurrent sources of congestion that cause the reliability issues present on each facility as the tool cannot completely account for such things as the effect of the large number of median openings on the traffic patterns in the US-31W networks. Caution must be exercised when using the USR estimated data as a baseline condition for project planning purposes. It must be made clear to users of this data and practitioners that the estimated data represents the average case of conditions present on the facility. If the reliability and congestion issues are related, in large part, to non-recurrent congestion sources such as accidents and unique traffic flow patterns, the USR may not be able to accurately capture the fine variation in day to day conditions on a facility.

3.2.4 Comparison of Measured and Estimated TTI and PHTTR

With the comparison of the base speed distributions completed and with the knowledge that the estimated data may reflect more of the average condition on each facility the travel time index and peak hour travel time ratio profiles for each network were generated.

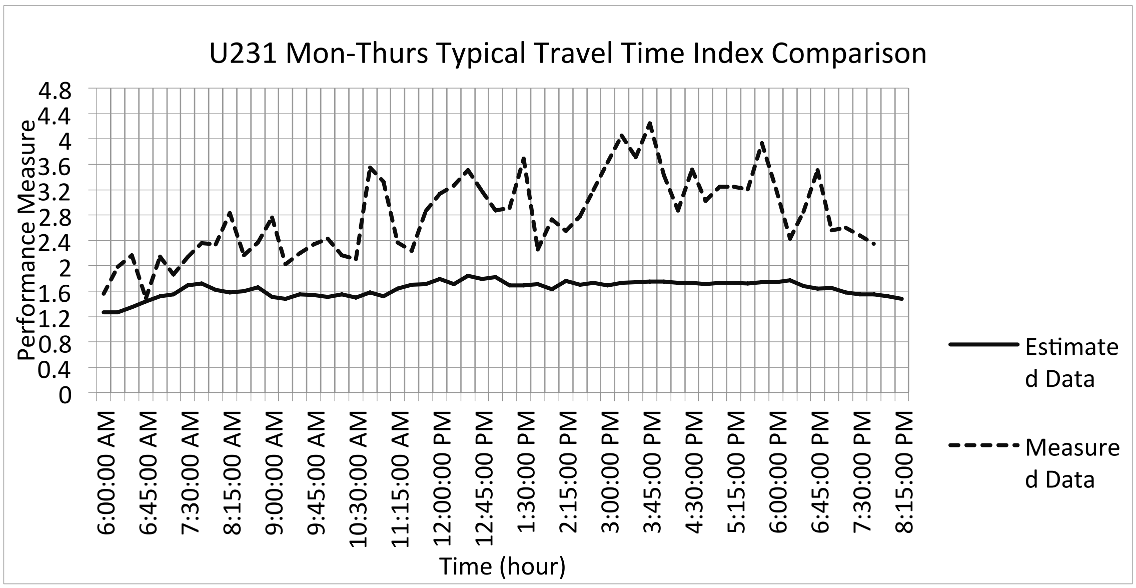


Figure 38: US-231 Mon-Thurs Travel Time Index using Estimated Data

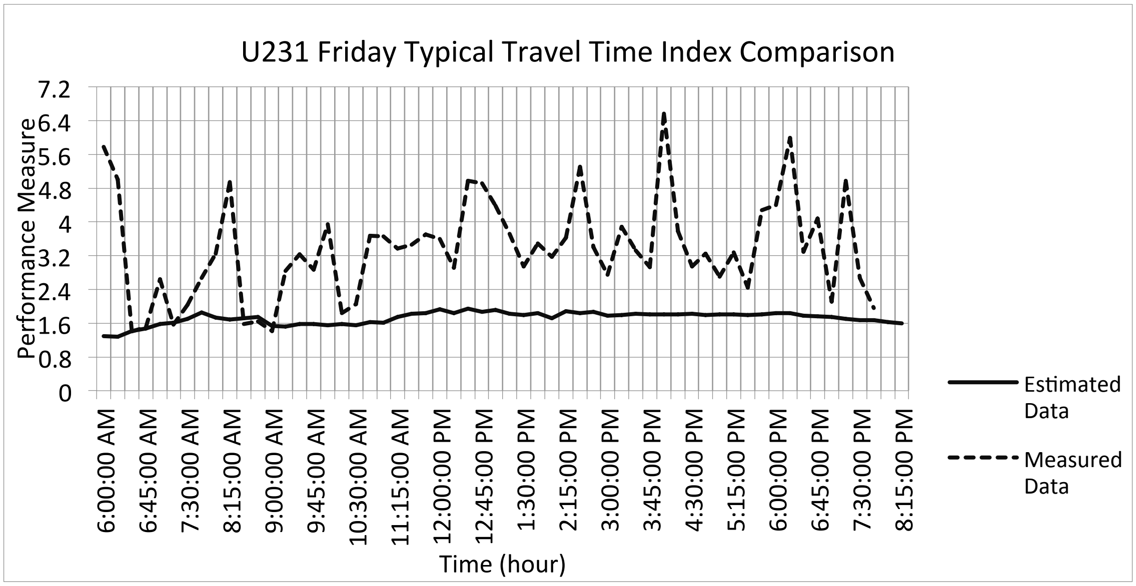


Figure 39: US-231 Friday Travel Time Index Comparison

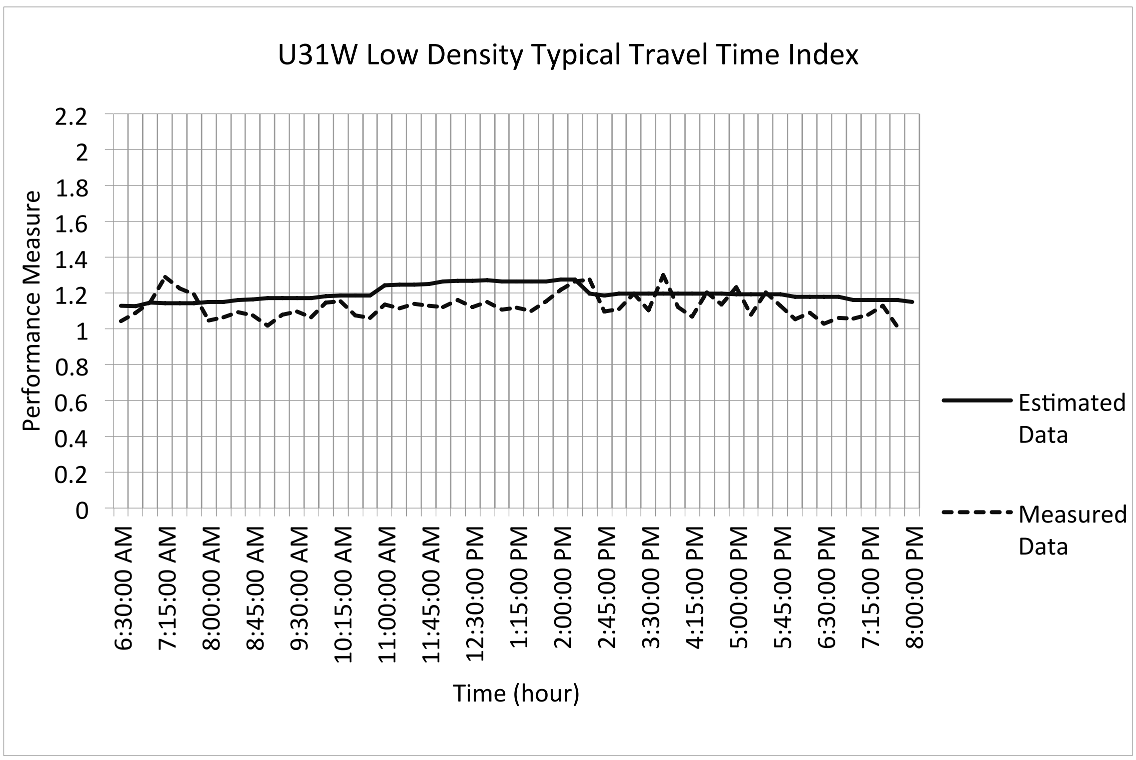


Figure 40: US-31W Low Density Travel Time Index using Estimated Data

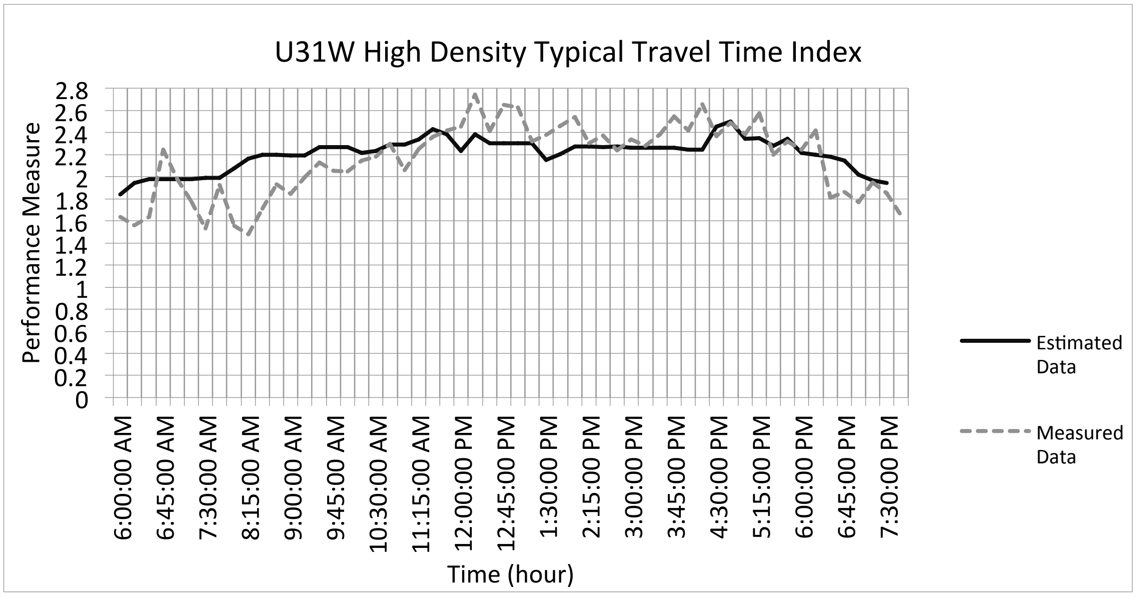


Figure 41: US-31 High Density Travel Time Index Using Estimated Data

From Figure 38 we see that according to the estimated data US-231 most often operates at LOS C during the AM and PM peak periods (using Table 3). This is in contrast to the measured data which show US-231 operates at LOS D and E respectively. While the measured and model data do not agree in this case, this can be explained by the increased average speed of the USR data. With the majority of speed records now being centered at a higher speed than what is normally achievable on the facility, measures such as the TTI will indicate decreased congestion. In these cases, caution should be used as the USR tool may indicate better conditions than those actually achievable on the facility.

In Figure 40 it is noted that the TTI based on the estimated and measured data compare well with both data sources estimating a LOS A/B throughout the day. Note that the estimated data shows a drop in TTI at the 2:30PM time period. This can be attributed to the change in signal timing plans during this period. As the change in signal timing plan causes a new *HCS 2010* network to be needed, the queue previously built up on the network is dissipated, effectively resetting the traffic volume on the network.

Figure 41 shows that the high density portion of US-31W is expected to operate at LOS D during the AM and PM peak periods. This is consistent with what was predicted using the measured TTI data presented above.

With the TTI values found the estimated data was used to produce the PHTTR. The process used to produce this performance measure involved selecting the highest hourly travel time during the peak period and dividing this by the free flow travel time or travel time at the speed limit. This process is described in further detail in section 3.1 above.

Table 9: Estimated Data PHTTR

PHTTR	US-231		US-31W High Density		US-31W Low Density	
	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak
Monday-Friday	---	---	5.58	2.44	1.04	0.88
Monday-Thursday	1.38	1.47	---	---	---	---
Friday	1.46	1.54	---	---	---	---

Table 10: Estimated Data PHTTR Based LOS

PHTTR	US-231		US-31W High Density		US-31W Low Density	
	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak
Monday-Friday	---	---	F	E	B	B
Monday-Thursday	C	C	---	---	---	---
Friday	C	C	---	---	---	---

Comparison of Table 8 and Table 10 how that the measured and estimated LOS based on the PHTTR and TTI generally agree on each network. This can be attributed to the narrowed speed distribution of the estimated speeds. In the case of the high density urban networks the majority of the estimated speed records are estimated to be around the mean of the measured speed data. This means that the "measured" travel time value used in both the TTI and PHTTR equations from the estimated data are very similar. Furthermore, the desired travel time in these cases is based on speeds between 75 (US-231) and 90 (low density segment of US-31W) percent of the speed limit. This is not significantly different from the travel time at the speed limit that is used in the TTI equation. This produces similar values of each performance measure.

3.2.5 Comparison of Measured and Estimated LOTTR and PTI

Along with the above performance measures, the LOTTR and PTI were also found for each facility using the estimated data. The estimated speeds were aggregated to the typical weekday and hourly levels for calculation. Percentile values were then selected for each hour from 6:00AM to 8:00PM (to encompass the time period when the networks operate under coordinated signal timings). 50^{th}, 20^{th}, and 5^{th} percentile values (corresponding to the 50^{th}, 80^{th}, and 95^{th} percentile travel times) were needed for the calculation procedure.

The level of travel time reliability metric was calculated first using equation 1. If a facility initially presented a LOTTR that was below 1.0 this value was replace with a value of 1. This action was taken to prevent abnormally low values of the LOTTR metric from being generated due to excessive differences in the 50th and 20th percentile speeds on the facility. The results are given in Figure 42-Figure 44.

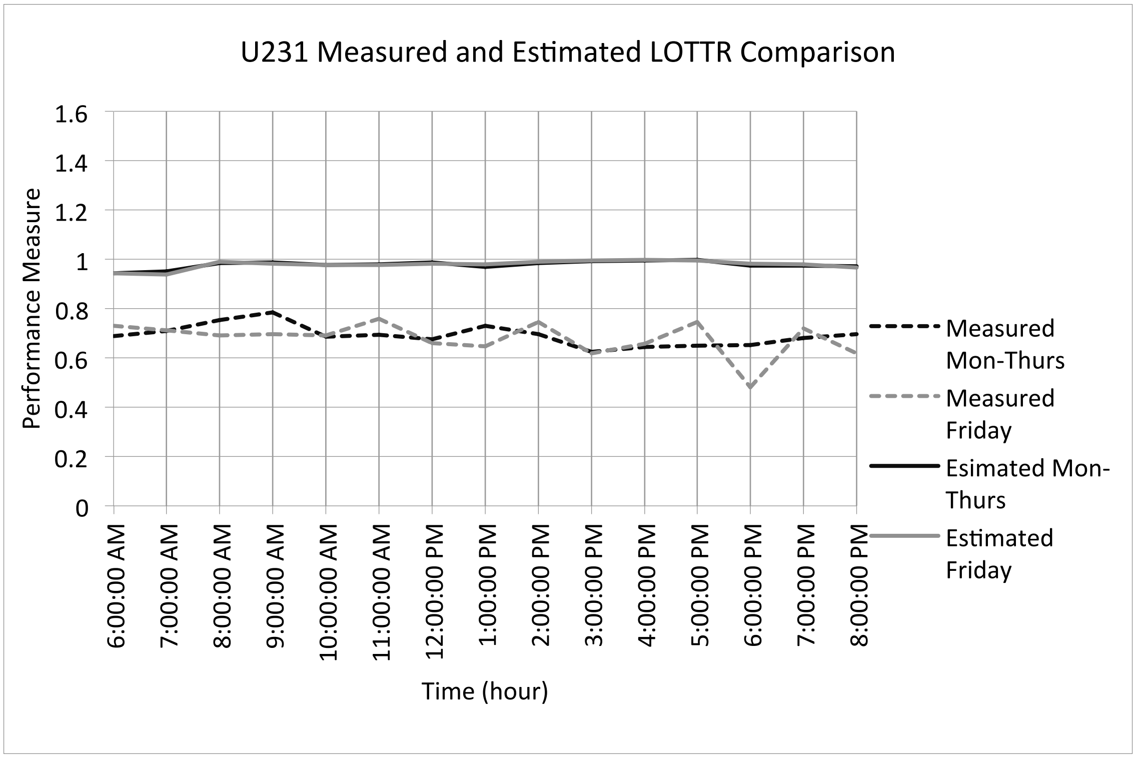


Figure 42: US-231 Measured and Estimated LOTTR Comparison

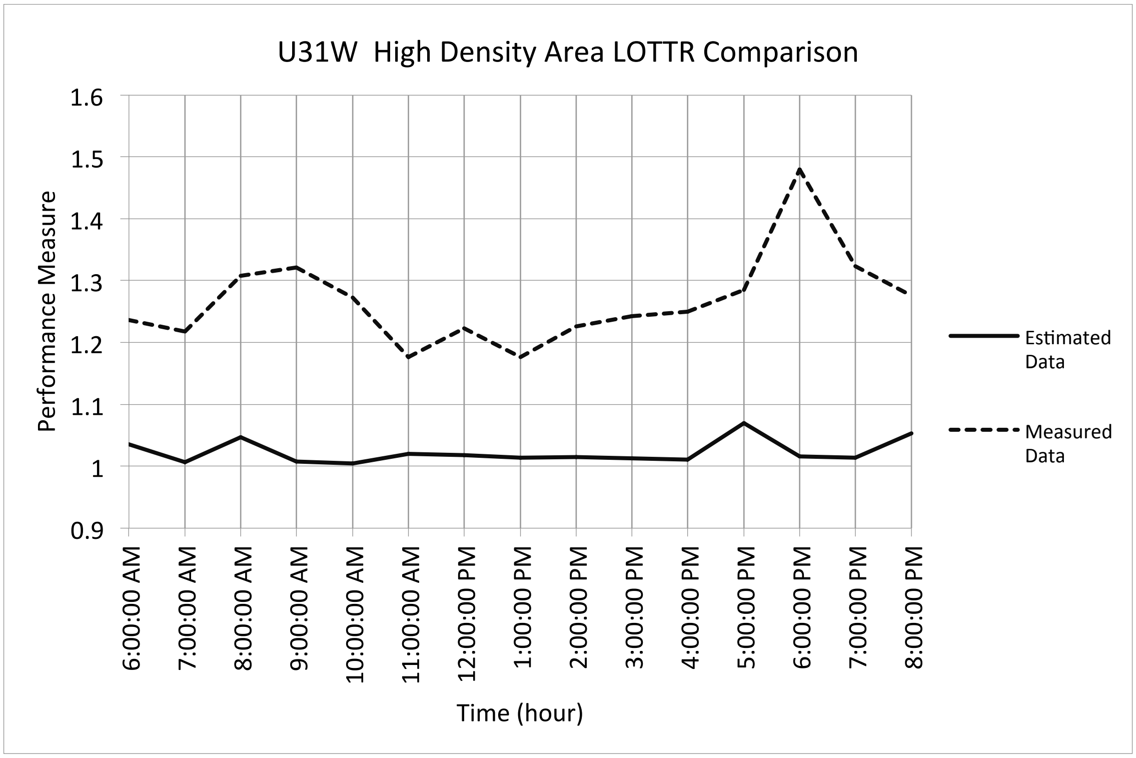


Figure 43: US-31W High Density Measured and Estimated LOTTR Comparison

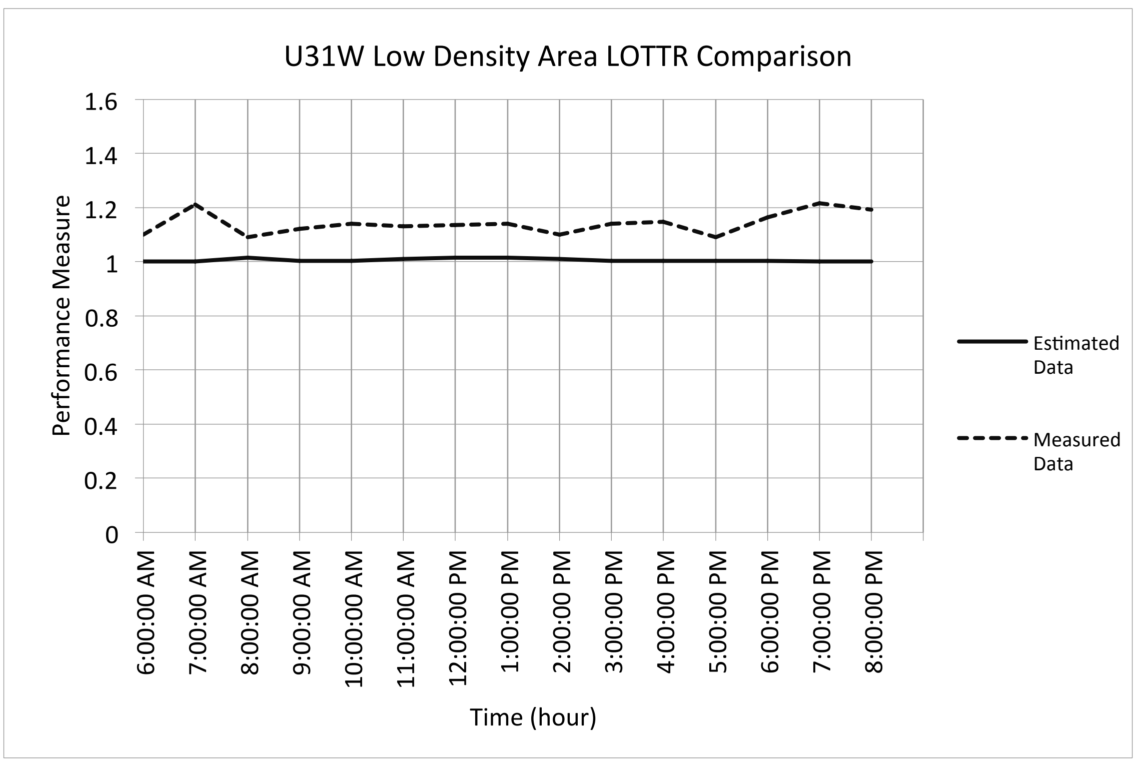


Figure 44: US-31W Low Density Area Measured and Estimated Data Comparison

In all cases the measured and estimated levels of travel time reliability agree. All facilities are shown to be operating under expected conditions (defined as having a LOTTR <1.5) for all periods during the day. In the case of the estimated data this was to be expected as the estimated speed distributions showed most of the speed records occurred at speeds near the center of the distribution. However, when the difference in the 50th and 20th percentile speeds decreases the values of the LOTTR metric falls. Caution is needed when using this metric as the difference in the 50th and 20th percentile speeds is underestimated in the estimated data then the reliability of the facility will be overestimated. This may lead to incorrect project decision making.

For the sake of comparison, the PTI was also calculated using both the measured and estimated speed data. The results are shown below in Figure 45-Figure 47.

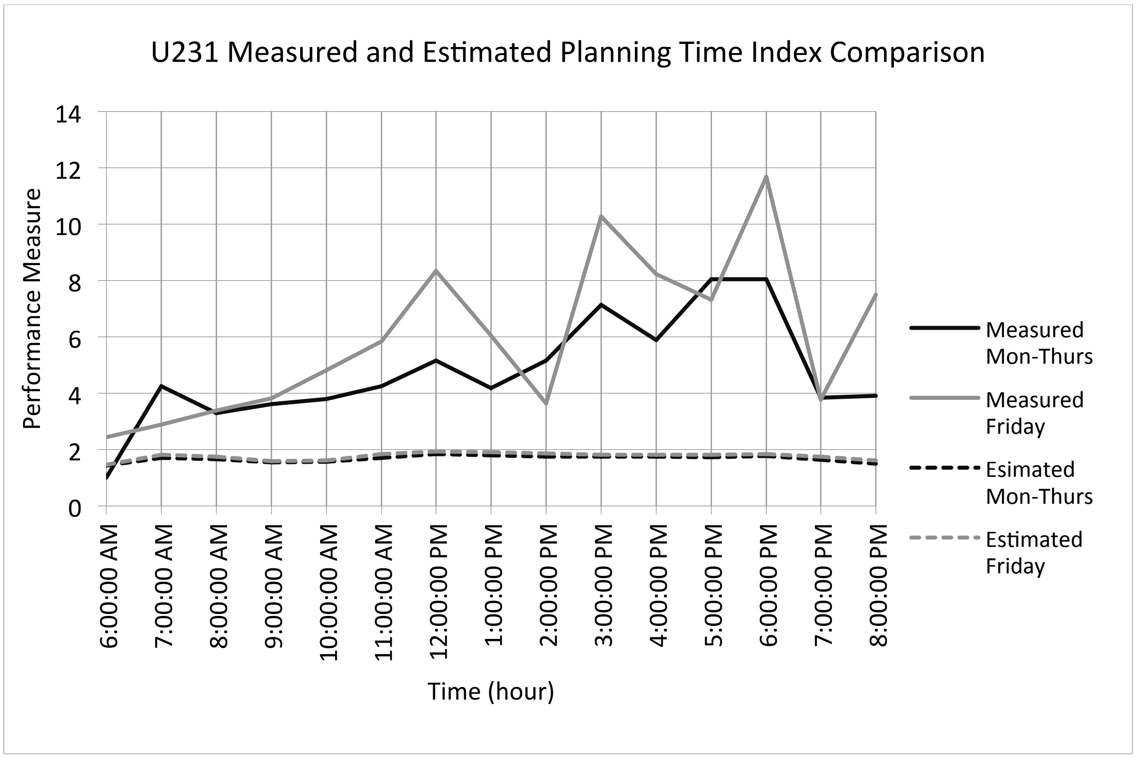


Figure 45: US-231 Measured and Estimated PTI Comparison

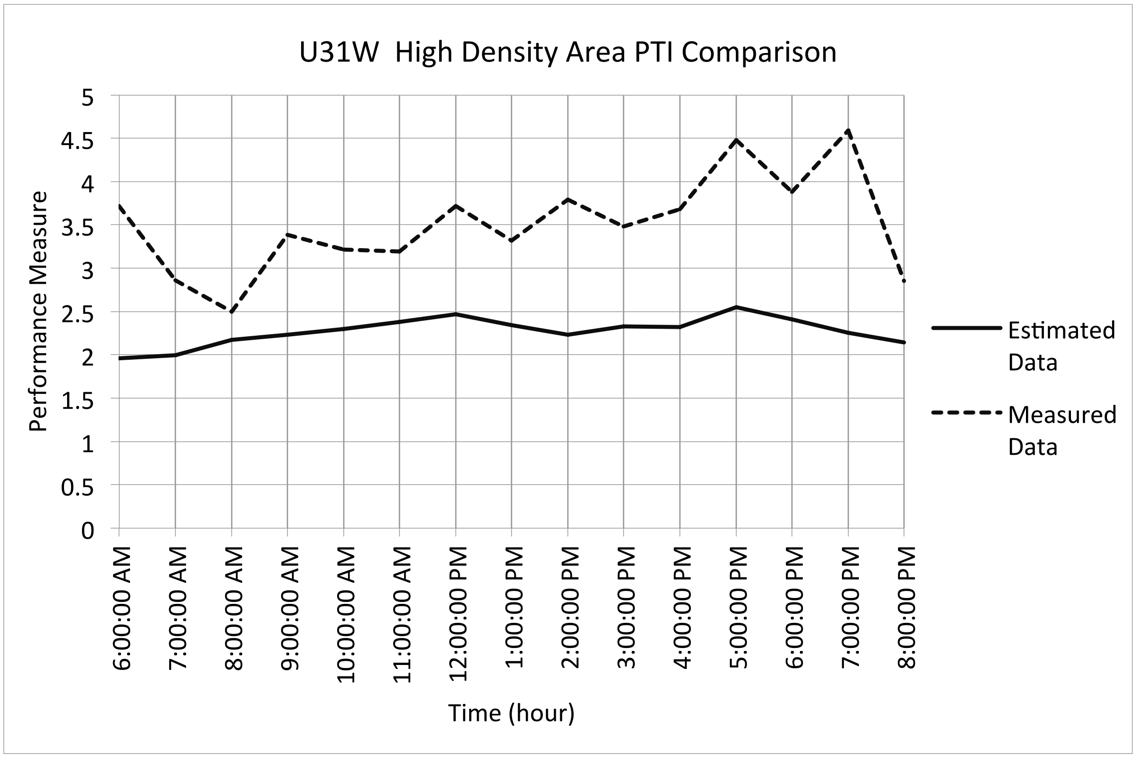


Figure 46: US-31W High Density Segment Measured and Estimated PTI Comparison

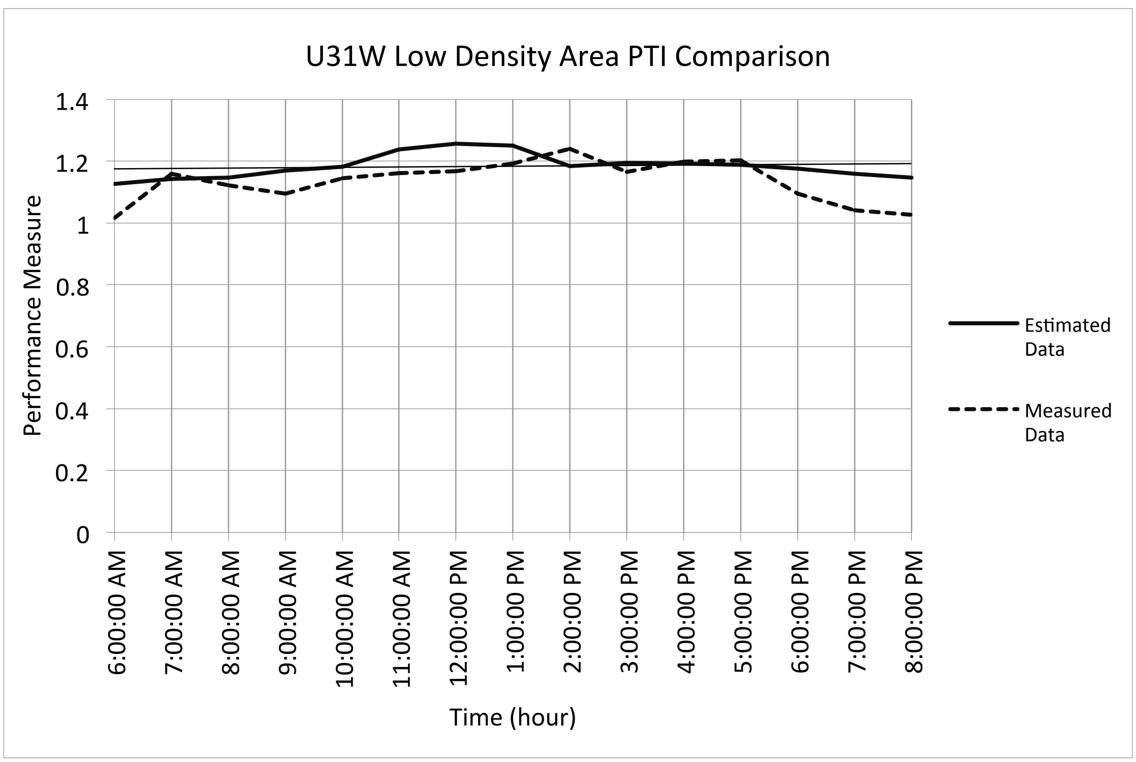


Figure 47: US-31W Low Density Segment Measured and Estimated PTI Comparison

In the case of the low density segment of US-31W the measured and estimated data compare well. This is logical as the estimated and measured speed distributions did not differ greatly between the measured and the estimated data. In the case of the high density portion of US-31W the measured and estimated metrics also compare well in that the two follow the same general pattern while the individual values of each metric throughout the day are different. This was expected due to the high, planning level nature of the USR tool. This also explains the difference is the estimated and measured performance metrics found on the US-231 site. As the USR is best able to produce a more average case, it is logical that the PTI metric based on USR data would follow the same general pattern as the measured data while not matching individual values throughout the day well. This is because the tool may sometimes not capture the unique day-to-day variations on the network while still accurately estimating the overall trend.

3.3 Examining the Effect of the *NPRM* Methodology on Performance Measures

With the model calibrated and a full year of estimated speed data (lacking any missing data points) generated further tests of the *NPRM* methodology were now possible. This section details one such test used to determine the effect of replacing differing levels of yearly speed data with the speed limit. Using Microsoft Excels random data function a random number was generated for each speed record on each network. These records were then sorted based on increasing randomly generated number. 25%, 50%, and 75% of the records were then replaced using the *NPRM* methodology (replacement with the speed limit).

As a means of examining the effect that this replacement methodology takes on the estimated speed data the CDF of the speed data before and after the adjustment is completed are examined below.

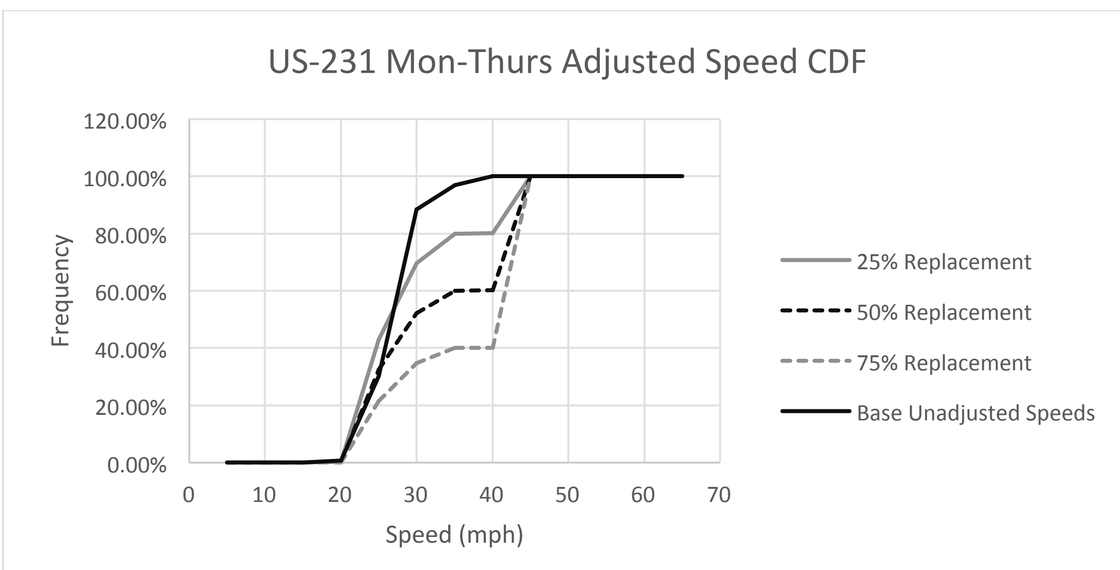


Figure 48:US-231 Mon-Thurs Adjusted Speed CDF Comparison

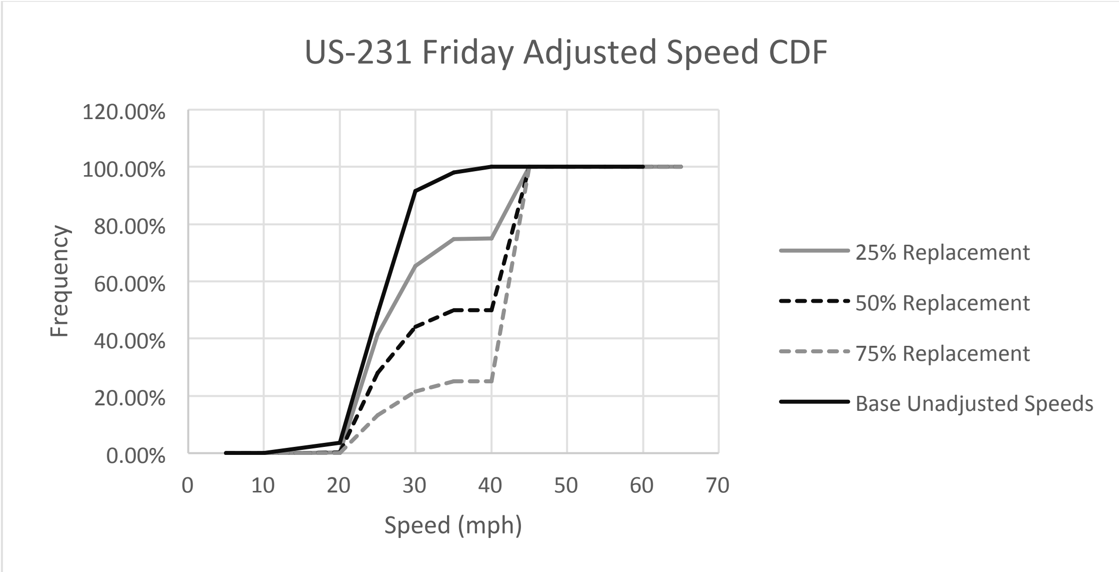


Figure 49: US-231 Friday Adjusted Speed CDF Comparison

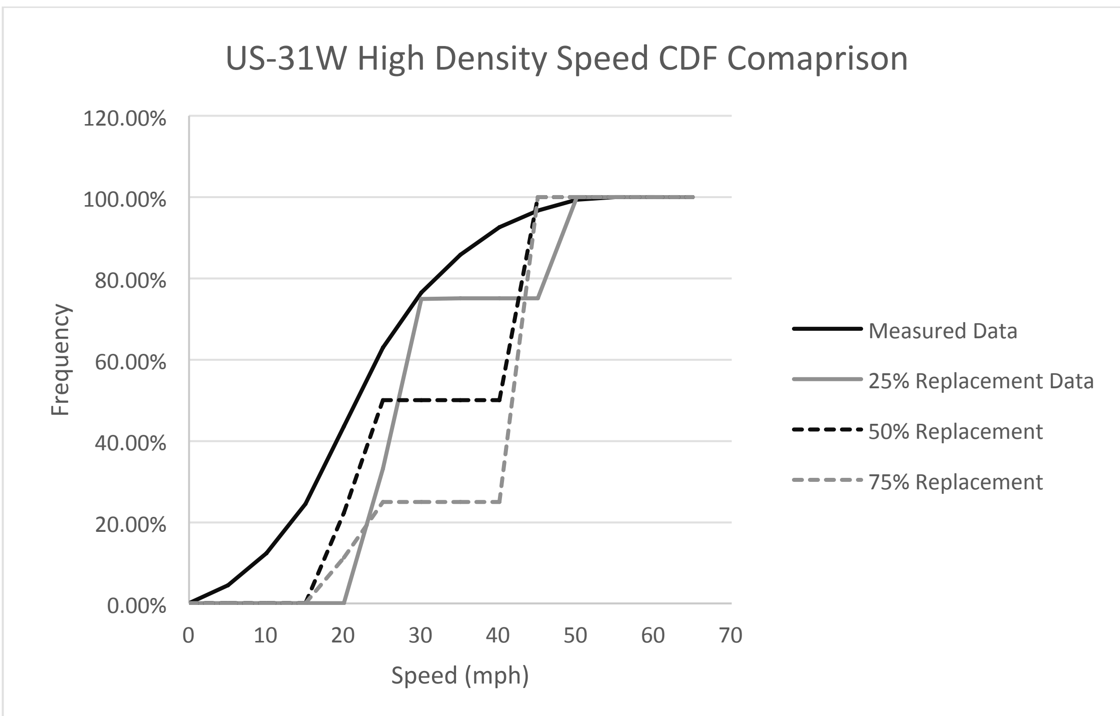


Figure 50: US-31W High Density Speed CDF Comparison

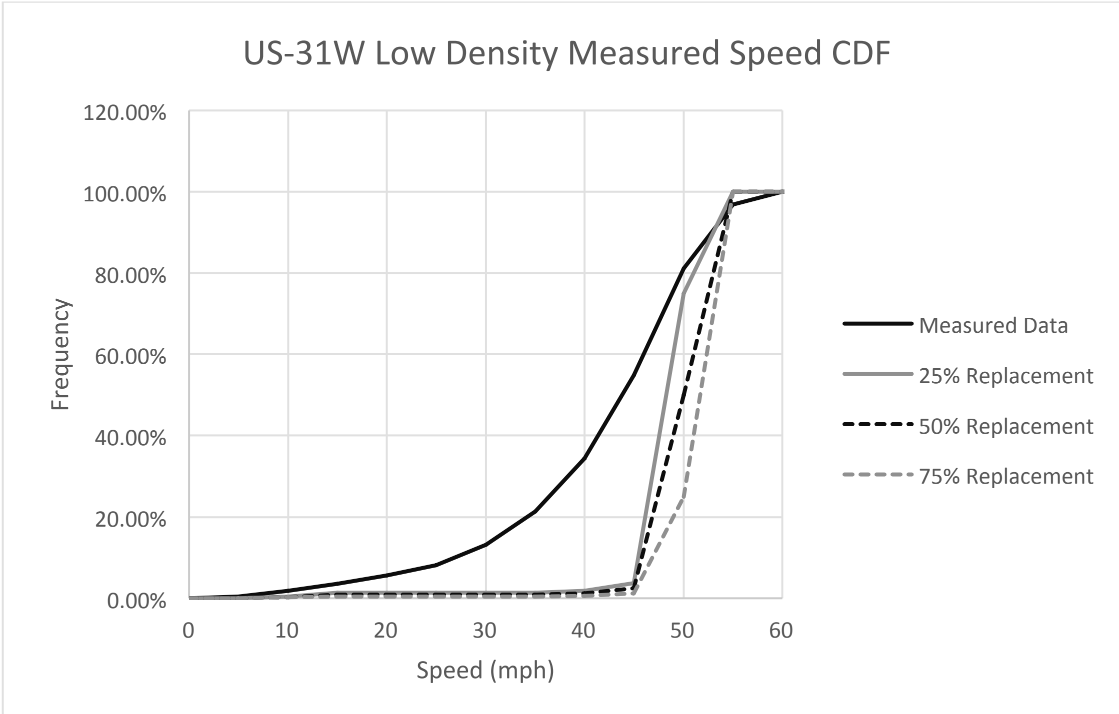


Figure 51: US-31W Low Density CDF Comparison

Creation of the CDF curves allow the comparison of percentile speeds. As these percentile speeds are used as inputs to the reliability performance measures inferences can be drawn about how the replacement methodology affects each measure based on its effect on the percentile speeds. As we can see in all cases the 85th percentile speed has risen from the measured 85th percentile speed more toward the speed limit. If the 85th percentile speed was used as the free-flow speed in these cases performance measures based on free-flow speed such as TTI would indicate a facility with worsened congestion than what is seen in reality. When the 50th percentile speed is examined the effect is the same. As the amount of data replaced with speeds records at the speed limit increases the 50th percentile speed approaches and finally reaches the speed limit. When this occurs metrics such as the level of travel time reliability that uses both the 85th and 50th percentile speeds will remain unchanged so long as the change in each percentile speed is relatively the same. When the 5th percentile speed is examined different effects are seen on the networks. In the case of US-231 where more speeds are in the low range of the distribution the effect of the added data is minimal. On the high-density portion of the US-31W network, as the majority of speed records occur in the 20-35 mph range, the effect of the replacement methodology is different based on the level of replacement. To be clear, all replacement levels (25%, 50%, and 75%) increase the 5th percentile speed seen on the facility. The 25% replacement level has the greatest impact, increasing the 5th percentile speed to nearly 4 times the original value. It is important to note that in this case using any of the 5th percentile speed values created after data replacement would indicate a facility operating at better levels of reliability than what are present in reality. In the case of the more rural segment of

US-31W the replacement of larger percentages of speed records with the speed limit increases the 5th percentile speed (and thus the 95th percentile travel time). Using this new 5th percentile speed would cause a lower PTI metric to be generated than what is really felt on the facility.

3.4 Evaluating Future Projects using the USR

In addition to the ability of the USR to generate current conditions on a subject facility the tool may also be used to estimate the effects of future projects before project implementation. In doing so performance measures may be generated related to the proposed project that allow engineers to determine which project of many will be the most beneficial to a facility. To this end three spot improvements detailed in *(2)* determined to be beneficial by CDM Smith Engineering were incorporated into the US-231USR model. Estimated future conditions based on current measured data were generated for each improvement and finally performance measures were calculated and used to determine which of the proposed projects provided the most improvement to the facility.

3.4.1 US-231 Spot Improvements

Three proposed spot improvements were examined for their benefit to the US-231 facility. These are 1) adding a left turn lane at the Greenwood Mall entrance onto US-231 opposite Bryant Way, 2) Providing dual left turn lanes from Cave Mill Road to US-231 combined with an extra through lane between Shive Lane and the frontage road 3) addition of a left turn lane from EB Pascoe Blvd onto US-231.

Figure 52-Figure 54 below taken from *(2)* show the proposed facility geometry to be used for each of the proposed improvements. These improvements are intended for implementation as a total suite of improvements implemented together to improve conditions on the facility.

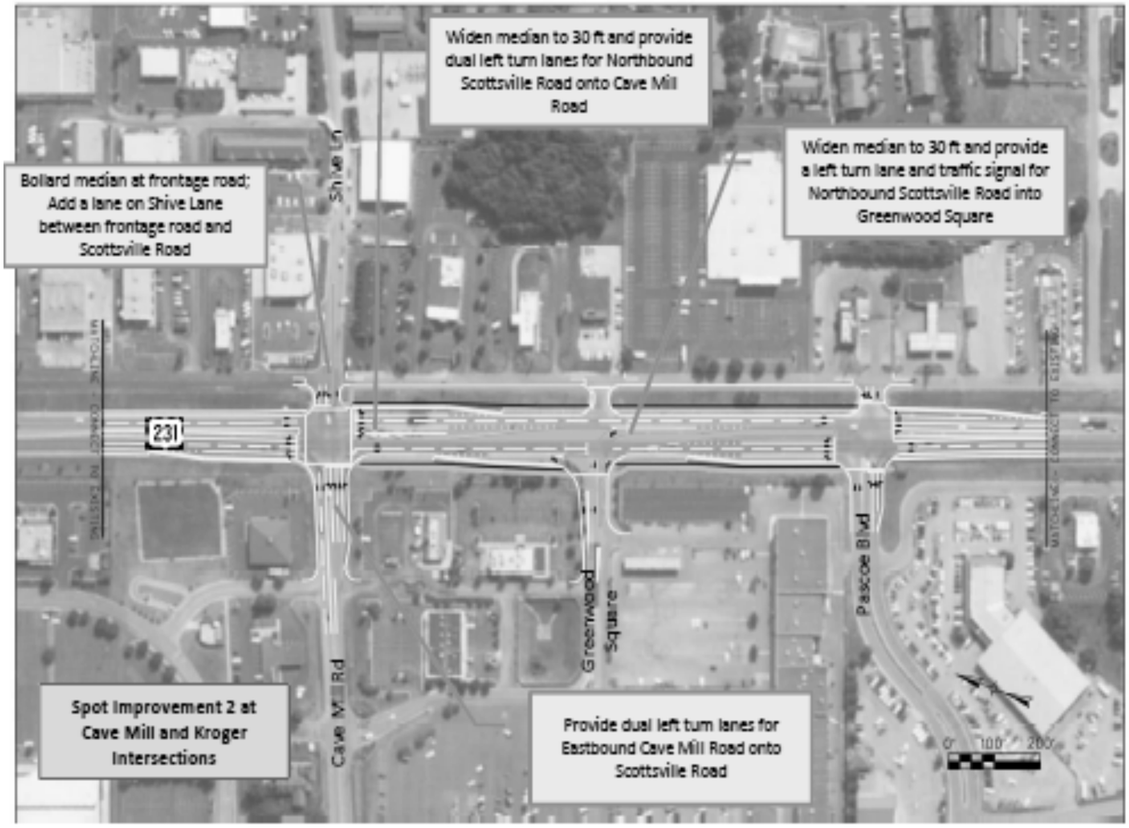


Figure 52: Cave Mill and Greenwood Mall Improvements

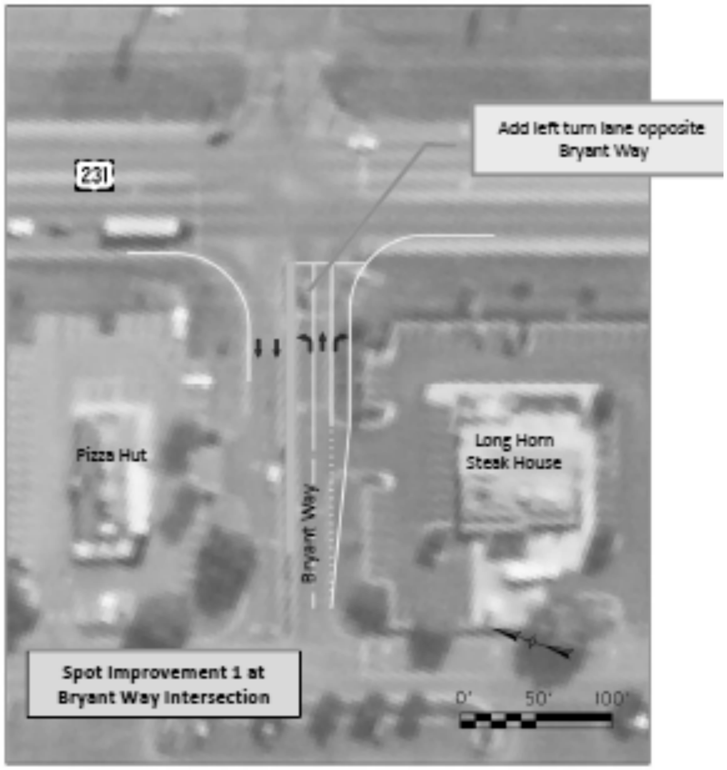


Figure 53: Bryant Way Spot Improvement

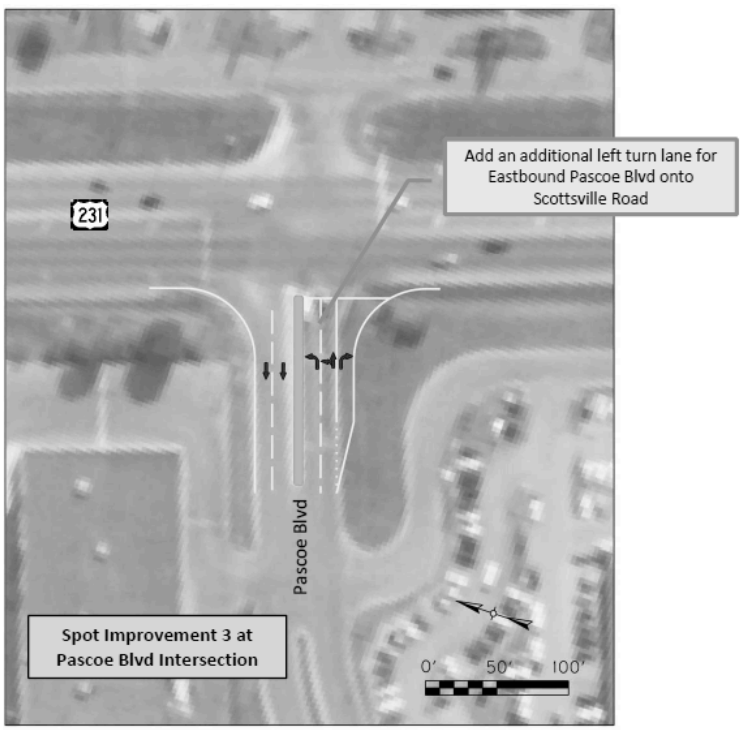


Figure 54: Pascoe Blvd Improvements

3.4.2 *Evaluating Proposed Treatments using the USR Tool*

Using the new facility geometry each of the proposed spot improvements were coded independently into a new US-231 Scottsville Road USR network. Each network implemented only one of the proposed improvements allowing the results of each improvement to be isolated. As no new signal timing data or measured volumes were available for the period after project implementation, the current measured conditions were used in coding the USR tool. Because of this the estimated data created herein based on these improvements must be used with caution as significant changes to the volume experienced on the facility and signal timing plans in place may occur as a result of project implementation. Figure 55 and Figure 56 present a comparison of the estimated speed current base data along with the estimated speed data after the implementation of each improvement.

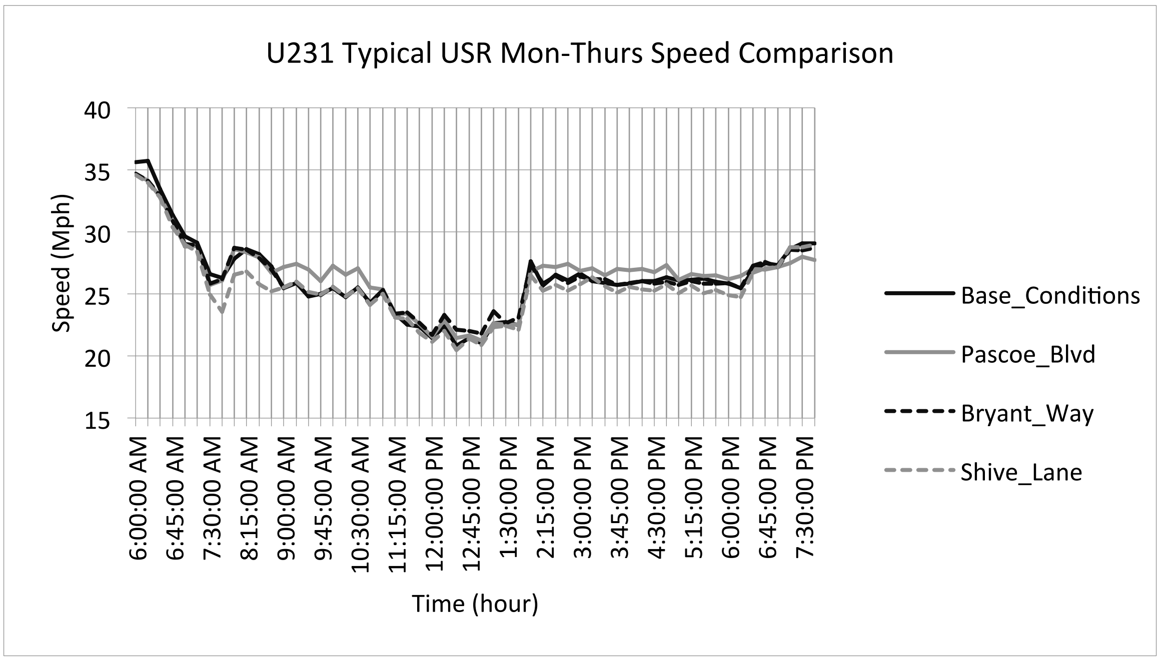


Figure 55: Estimated Mon-Thurs Improvement Data

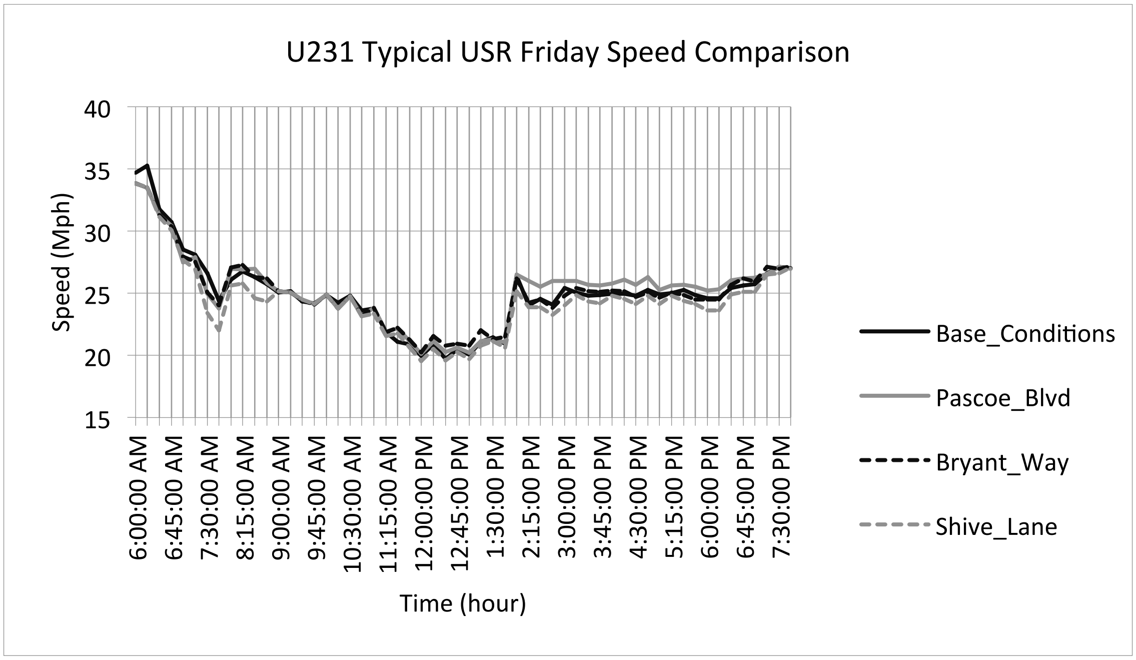


Figure 56: Estimated Friday Improvement Data

It can be noted that in each figure the estimated improvement data is generally near or below the base estimated data. The improvement data generated for the Pascoe Way changes shows a slight increase in the projected speed data as compared to the base data and the other projected improvement data. The decrease in the other estimated speeds is due to the increased volume from the side streets and the frontage road through the added turn lanes on the facility. This allows more vehicles onto the facility without the alteration of the current signal-timing plan in place at each intersection.

However, comparison of only these performance measures does not give the entire picture of reliability on the facility. While it is true that the proposed improvements appear to increase congestion based on the above performance measures it is important to note that this analysis is based on the mainline only. When selecting an improvement project for future consideration it is important to consider all portions of the transportation network that will be affected by the project. The addition of extra turn lanes, for example, would allow more left turn vehicles to move at the same time during the left turn phase from the side street. This would alleviate the large queues present on the side street locations and allow the left turn phase to be given lower amounts of green time (as the same number of vehicles now share two lanes). This extra green time could then be allocated to the main line through movement.

Due to the limited data output items generated by the tool and the limited resources available the examination of the side street conditions on the facility was not possible at this time. Future research is needed before final project selection to estimate the proposed improvements effect on the mobility and reliability of the transportation system as a whole.

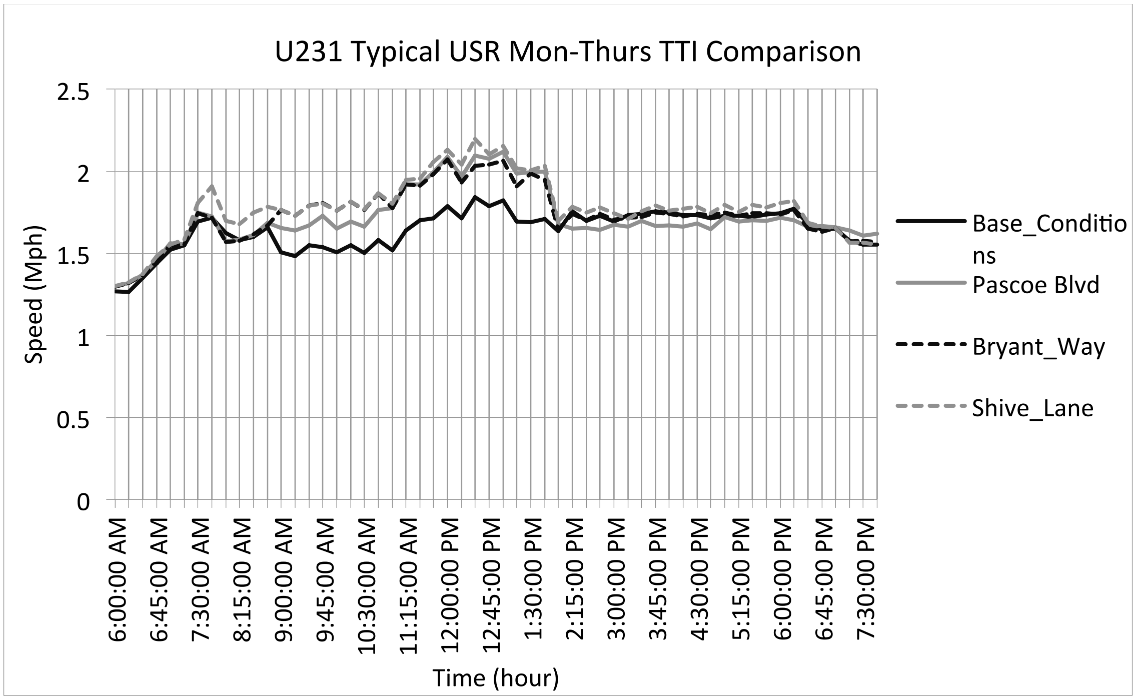


Figure 57: Typical Mon-Thurs TTI comparison of Proposed Improvements

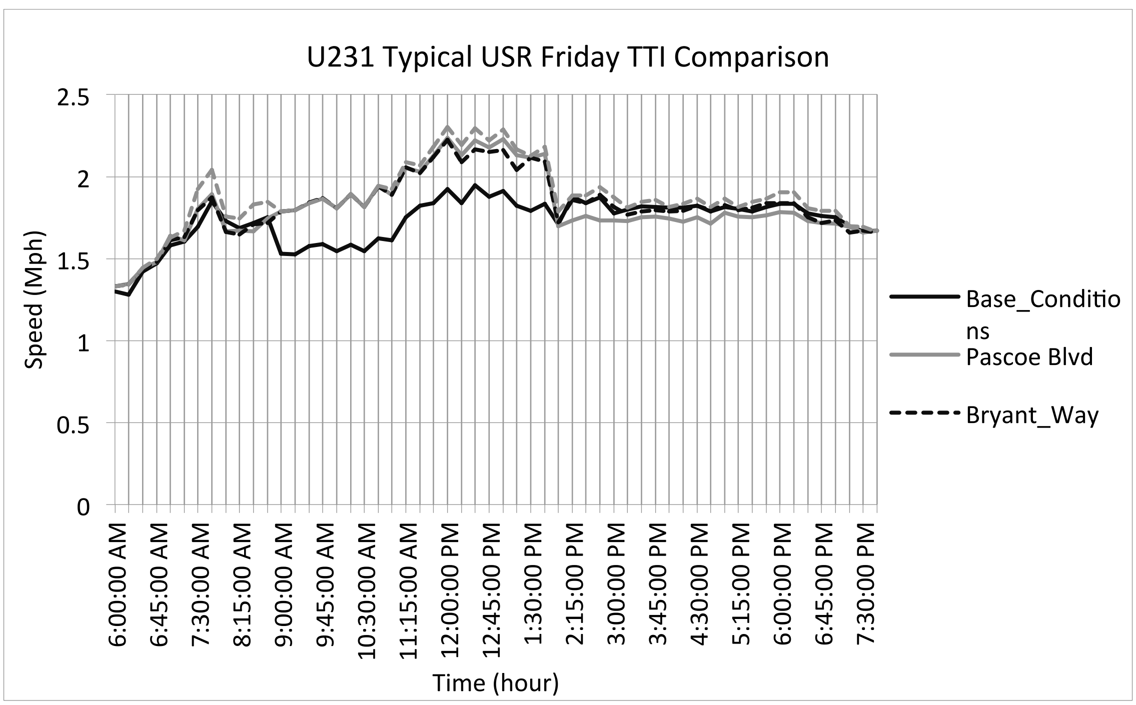


Figure 58: US-231 Typical Friday TTI Comparison for Proposed Improvements

Based on these comparisons all improvements increase congestion on the facility to some degree. However, comparison of only these performance measures does not give the entire picture of reliability on the facility. While it is true that the proposed improvements appear to increase congestion based on the above performance measures it is important to note that this analysis is based on the mainline only. When selecting an improvement project for future consideration it is important to consider all portions of the transportation network that will be effected by the project.

CHAPTER 4 SUMMARY AND FUTURE RESEARCH

In this thesis arterial travel time reliability performance measures were examined in depth. A first of its kind comparison was conducted examining the difference between the TTI, PTI, and *NPRM* proposed arterial travel time reliability performance measures. This comparison was conducted in order to examine the validity of the proposed measures for arterial reliability applications. By equating each performance measure to the categorical LOS metric found in the *HCS 2010* a direct comparison was made possible. Based on these tests it can be concluded that the PHTTR and LOTTR match the PTI and TTI more closely on the more rural, low signal density portion of the US-31W network as compared to the more urban segments examined herein. It was also found that the proposed metrics produce a more average level estimate of the facility conditions than the TTI and PTI. This calls for further research into the ability of these measures to accurately gauge reliability on urban arterial corridors.

Furthermore, it has been shown that the proposed performance measure "peak hour travel time ratio", when calculated for the hours called for in the *NPRM* may not give a true picture of the reliability of a facility. When networks such as the high density portion of US-31W are concerned the true peak period occurs during the noon hour. As such calculating the PHTTR metric for the traditional peak hours indicates a reliable facility when in reality significant reliability issues exist that are not being captured. Future research is needed to establish a methodology to capture the true peak period of a facility using the PHTTR (if that peak is outside of the traditional peak periods called for).

Third, an examination of the *NPRM* methodology for speed record replacement was conducted. It was shown that when using this methodology, the speed distribution of the facility narrows toward the speed limit. Furthermore, this narrowing of the distribution may cause an inaccurate view of facility reliability by reporting a facility as being more reliable that it truly is. These tests lead us to conclude that the proposed performance measures are limited in their ability to give a clear picture of the reliability of a facility. Further research is needed to fully vet the application of the proposed performance measures with respect to arterial reliability measurement.

Finally, in chapter 3 above an examination was conducted using the *Urban Streets Reliability Module* to determine its capacity to estimate current and future conditions on subject facilities based on current measured data. Using current weather, accident, geometry, and volume data, speed and travel time records on each facility were generated. Comparison of this data to the measured data revealed that the USR generated conditions on each facility represent a mean or average of the current measured conditions. Future conditions after the implementation of three proposed improvements to the US-231 corridor were also examined. It was shown that the USR is capable of producing future data records that may be used to aid in performance measure calculation and project selection. Future lines of research were also proposed related to using the USR tool to generate metrics for side streets as well to determine the benefit posed by each improvement on the transportation network as a whole.

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VITA

- Galen T. M. Smith
- Place of Birth: Whitesburg, KY
- Educational Institutions attended:
    - Transylvania University: Bachelor's of Arts
    - University of Kentucky: Bachelor's of Science in Civil Engineering
- Professional Positions Held:
    - University of Kentucky: Graduate Research Assistant to Dr. Mei Chen
    - University of Kentucky: Teaching Assistant to Dr. Mei Chen
- Scholastic Honors:
    - University of Kentucky:
        - Chi Epsilon Engineering Honor Society
    - Transylvania University:
        - Morrison Scholarship Recipient
        - Senior Challenge Award Winner