RESEARCH & DEVELOPMENT

Analytical and Predictive Approaches for Quantifying Reliability Performance of Arterial Streets

Thomas Chase, MSCE, P.E.
Behzad Aghdashi, Ph.D.
Dezhong Xu, MSCE
Guangchuan Yang, Ph.D.
Juwoon Baek
Billy Williams, Ph.D., P.E.
Institute for Transportation Research & Education,
North Carolina State University

Bastian Schroeder, Ph.D., P.E.
Lake Trask, Ph.D.
Kittelson and Associates, Inc.

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16. Abstract

Arterial streets are a critical location of travel delays in urban transportation systems. This project focuses on the analytical and predictive approaches for quantifying reliability performance of arterial streets to enable incorporation of travel time reliability into arterial planning and management in North Carolina. A series of analyses on the sources of arterial unreliability is presented which also critically examines the differences in data sources available on North Carolina arterials. Two NCDOT arterial analysis tools were updated to allow for planning-level arterial reliability analysis and prioritization of traffic signal retiming in the state.

The analyses presented in this report may be repeated by NCDOT staff using a number of sources and platforms available to NCDOT including NCDOT's SPM tool and Retiming tool, RITIS Probe Data Analytics, ClearGuide, and FHWA's National Performance Management Data Research Data Set. Utilization of the ARTVAL tool will enable planning-level HCM arterial reliability analysis of corridors with a limited data requirement. The utilization of the analyses and tools developed in this project will allow NCDOT to include travel time reliability in planning, managing and improving arterials in the state and measure the additional benefits to the public from these programs.

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EXECUTIVE SUMMARY

The state of North Carolina is one of the fastest growing states in the U.S. According to the U.S. Census Bureau, North Carolina ranked fourth in numeric population growth in 2019 (1). With expected continued population and development growth for the state, managing traffic across freeways and arterials continues to be of vital importance for the North Carolina Department of Transportation (NCDOT). Specifically, identifying and addressing high-congested and low reliability facilities will play an increasingly crucial role in addressing public concerns and managing congestion levels across the state. Arterial streets are a critical location of travel delays in urban transportation systems. Thus, the performance assessment of the arterial streets is necessary and important.

This project focuses on the analytical and predictive approaches for quantifying reliability performance of arterial streets. A series of analyses on the sources of arterial unreliability is presented which also critically examines the differences in data sources available on North Carolina arterials. Two NCDOT arterial analysis tools were updated to allow for planning-level arterial reliability analysis and prioritization of traffic signal retiming in the state.

The analyses presented in this report may be repeated by NCDOT staff using a number of sources and platforms available to NCDOT including NCDOT's SPM tool and Retiming tool, RITIS Probe Data Analytics, ClearGuide, and FHWA's National Performance Management Data Research Data Set. Utilization of the ARTVAL tool will enable planning-level HCM arterial reliability analysis of corridors with a limited data requirement. The utilization of the analyses and tools developed in this project will allow NCDOT to include travel time reliability in planning, managing and improving arterials in the state and measure the additional benefits to the public from these programs.

Further research into arterial reliability would benefit greatly from the utilization of additional traffic signal data which are planned to be available through NCDOT's Advanced Traffic Management System or Automated Traffic Signal Performance Measures platform. This analysis would provide additional insight into the reliability impacts of signal timing settings and time of day plan transitions.

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1. Introduction

The state of North Carolina is one of the fastest growing states in the U.S. According to the U.S. Census Bureau, North Carolina ranked fourth in numeric population growth in 2019 *(1)*. With expected continued population and development growth for the state, managing traffic across freeways and arterials continues to be of vital importance for the North Carolina Department of Transportation (NCDOT). Specifically, identifying and addressing high-congested and low reliability facilities will play an increasingly crucial role in addressing public concerns and managing congestion levels across the state.

Arterial streets are a critical location of travel delays in urban transportation systems. Thus, the performance assessment of the arterial streets is necessary and important. In practice, it was found that most travelers were more frustrated with unexpected delays than the recurrent everyday congestion. Therefore, instead of an average time for travel throughout the year, travel time reliability (TTR) has become an important measure to evaluate the effectiveness of transportation systems *(2,3)*. Recently, both federal rulemaking agencies and public expectations are moving away from traditional, traffic-engineering focused congestion measures towards more user-experience based measures describing the reliability and variability of travel times *(4,5)*. To date, there have been considerable research efforts that leveraged the historic probe-based data for evaluating the TTR on freeway systems *(6,7)* as well as predictive approaches for quantifying reliability for future projects and improvements *(8,9)*. In comparison with freeways, arterial streets are more complex systems, where the varying demand levels, changes in signal timing, and the potential for incidents and work zones can drastically affect the performance and reliability of arterial streets *(10)*. In addition, performance measures reported via probe-based data sources are not fully validated for arterial streets. Earlier efforts have identified potential under-reporting of delays at traffic signals, as probes that are stopped in a queue are less likely to be reflected in the aggregate probe data set *(11)*. To truly evaluate the reliability of arterial facilities, and before using TTR to guide decision-making and policy, the quality of the probe-based data also needs to be verified.

This report focuses on the analytical and predictive approaches for quantifying reliability performance of arterial streets. By analyzing various potential reliability impacting factors, the researchers found out that different data sources have isolated sensitivities to different dynamics of the traffic. The study analyzed multiple potential factors that may impact the arterial reliability by using probe-data. Two tool updates were performed on existing NCDOT tools used in the analysis of arterial performance. ARTVAL is an HCM-based planning level arterial analysis tool originally developed in Excel. This project developed a web-based platform and update the tool to include additional user experience and default input improvements which allow for the planning-level reliability analysis of arterials. NCDOT's Signal Performance Measure tool was also updated to include additional analysis types and new travel time data.

The report includes a detailed methodology used to analyze the arterial reliabilities is introduced in the third chapter. Chapter four contains the development of NCDOT Signal Performance Measure Tool update. The ARTVAL tool update is documented in Appendix A. The conclusions, recommendations, and future research will be introduced in the last section.

2. Literature Review

Currently, the majority of arterial TTR research efforts have been focused on identifying the effects of traffic control devices, traffic incidents, work zones, adverse weather conditions, that time of day, day of the week, and holidays on arterial travel time and travel time reliability *(12-15)*.

Polus *(16)* defined travel time and operational reliability on arterial routes as the consistency of operation of the route, which is the inverse of the standard deviation of the travel time distribution. The research assumed that travel time on arterials following a gamma distribution, based on which, TTR measure could be estimated through regression modeling. Taylor and Somenahalli *(17)* further discussed the potential issues with travel time variability distribution pattens. Based on field data, the research found that there is a bimodality in the actual travel time distributions, which is mainly caused by the probability of encountering delay or not at traffic signals. This bimodality tends to affect the measurement of travel time variability and reliability and needs to be taken into account when measuring TTR. Similarly, Yang et al. *(18)* found that travel time distribution of interrupted flow displays a bimodal pattern rather than a unimodal curve, thus arterial travel time could be divided into an uninterrupted component and an interrupted component. The research investigated six convex distributions and confirmed that travel time under interrupted flow generally follows a bimodal distribution and emphasized that intersection control delay has a critical role in arterial TTR.

Then, some analytical modeling studies have been conducted to analyze arterial TTR, such as Pu *(19)* analyzed the mathematical relationships and interdependencies between various TTR measures. The research recommended using the coefficient of variation, instead of the commonly used standard deviation, as a proxy for other reliability measures. Besides, the research recommended using the median-based buffer index or the failure rate as TTR measures. Li et al. *(20)* employed GPS speed profile data to study TTR on arterial road segments based on the stochastic dominance theory, which captured the commonality of all individuals who had similar risk-taking preferences. Results showed that conservative travelers have to pay a risk premium such as an extra buffer time to achieve the same on-time arrival probability. Zhang et al. *(21)* compared the quality of arterial travel time acquired from GPS probe and Bluetooth data. The research pointed out that travel time on arterials tends to have a higher variation than that on freeways, thus recommended using the coefficient of variation to assess TTR. Zheng et al. *(22)* developed a network travel time distribution model based on to field travel time data, which investigated the network-level TTR by using weighted standard deviation of travel time rates and weighted skewness of travel time distributions. Glick and Figliozzi *(23)* employed transit GPS data to estimate arterial travel speed percentiles and associated confidence interval, where time-space speed profiles and heat maps were employed to visualize road segments and intersections that have high travel time variability. Singh et al. *(24)* conducted a case study on the travel time variability and reliability using travel time data collected by Wi-Fi sensors at an urban arterial. It was found that that travel time variation is significantly influenced by the time of the day and day of the week. Tufuor and Rilett *(25)* presented a validation study of the Highway Capacity Manual (HCM) urban street TTR methodology based on travel time distribution data collected by Bluetooth. The research found that there were statistically significant differences but no significant practical differences between the HCM and the empirical travel time distributions. However, the research pointed out that the HCM travel time distribution had a lower variance than the empirical distribution and thus tends to underestimate the TTR metrics.

Besides, there are also some simulation-based research that employed microsimulation modeling to investigate arterial TTR. Elefteriadou et al. *(26)* developed two arterial travel time estimation models using CORSIM microsimulation results to estimate travel time under congested and uncongested traffic scenarios. These two models were validated via real-world travel time data, the modeling results were eventually used for analyzing TTR measures on arterials and figured out potential issues that may affect the assessment of arterial TTR *(27)*. Tottisi et al. *(28)* proposed a methodology to estimate urban road network TTR using historical radar-detector data and a real-time traffic simulation model. Statistical measures such as coefficient of variation and congestion index were employed to assess the TTR of different roadway systems including individual arterials, small-scale and large-scale road networks.

3. Methodology

3.1 Evaluation Framework

3.1.1 Factors Affect Reliability

This research first identified factors that have the potential to affect arterial reliability through theoretical analysis and engineering judgement. The initial candidate factors include:

- Severe weather
- Signal timing optimization
- Active traffic management
- New developments
- Seasonal demand fluctuation
- Arterial coordination
- Access management, and
- Incidents

These factors are considered as contributing to the recurring and/or non-recurring congestions on arterials. To quantify the impacts of each factor on arterial reliability, each factor was analyzed at isolated selected sites. Multiple data sources were used during the analysis to avoid errors caused by a single data source and examine differences in data.

3.1.2 Data Sources

This research employed the following data sources for arterial reliability analysis: the INRIX traffic data, the HERE.com traffic data, the National Performance Management Research Data Set (NPMRDS), the Intelligence to Drive (i2D) in-vehicle tracker, and the National Oceanic and Atmospheric Administration (NOAA) weather data.

Each data source has its own advantage on different analyzing perspectives. For instance, INRIX and Here.com data could be used to analyze the arterial reliability by comparing arterial travel time and speed. NPMRDS could provide additional necessary information for reliability analysis. At the microscopic level, i2D contains high resolution trajectory data and provides detailed vehicle kinematics data such as instantaneous speed, vehicle position, and acceleration for each vehicle however it is only available in instrumented vehicles *(29)*. NOAA data, as a complementary data source, will help this research with analyzing the impact of non-recurrent weather events on arterial traffic reliability.

3.1.3 Site Selection

In this section, we talk about sites that we can assess reliability impacting factors, and potentially show some additional information such as data source for each site in a matrix format.

Table 1 documents the selected sites for each analysis purpose. These sites are majorly located in Raleigh, Cherokee, Asheville, Charlotte and Wilmington in North Carolina. Travel time data collected from sites located in tourism cities such as Asheville, Cherokee, and Wilmington were analyzed to investigate the impact of seasonal tourism traffic on arterial reliability. Urban areas usually have major traffic generation and attraction facilities, such as universities, supermarkets and business plazas, which are expected to create significant seasonal traffic (i.e., school and no-school seasons) and peak hour traffic patterns. Active Traffic Management (ATM) strategies are often deployed in metropolitan areas to address traffic congestion and improve travel time reliability. With these concerns, the sites used to analyze Seasonal Effects, Peak Pattern and ATM strategies were selected from metropolitan (Raleigh and Charlotte). Sites used to analyze the weather impact were selected from multiple cities. To minimize the influence from other potential factors, all selected sites are away from trip generation and/or attraction facilities. Finally, sites that contain both probe data and trajectory data were selected to analyze the reliability of probe data.

Table 1 - Use Cases with Assigned Sites

Impact Factor	Data Collection Site(s)
Peaking Pattern	- Western Blvd, Raleigh (Site #1)
Seasonal Effects	- US 19, Cherokee (Site #2) - US 441, Cherokee (Site #3) - US 421, Wilmington (Site #4) - Hendersonville Rd, Asheville (Site #5)
ATM strategies	- Leesville Rd, Raleigh (Site #6) - Creedmoor Rd, Raleigh (Site #7) - Six Forks Rd, Raleigh (Site #8) - Hendersonville Rd, Asheville (Site #5)
Quantifying impacts of new development	- US 64, Raleigh (Site #9) - US 70 Business, Smithfield (Site #10)
Isolating effects of severe weather	- US 25 (North of I-214), Asheville (Site #11) - US 25 (Inside I-214), Asheville (Site #12) - US 70, Asheville (Site #13) - NC 191, Asheville (Site #14) - College Rd, Wilmington (Site #15) - Military Cutoff Rd, Wilmington (Site #16) - US 17, Wilmington (Site #17) - N. Garham St. Charlotte (Site #18) - NC 16 Brookshire (North), Charlotte (Site #19) - NC 16 Providence (South), Charlotte (Site #20) - Capital Blvd, Raleigh (Site #21) - Falls of Neuse Rd, Raleigh (Site #22) - US 70 RDU (North), Raleigh (Site #23) - US 70 Gamer (South), Raleigh (Site #24)
Probe compared to High Resolution Vehicle Trajectories	- Avent Ferry Road Site 1, Raleigh (Site #25) - Glenwood Ave Site 1, Raleigh (Site #26) - Tryon Rd Site 1-4, Raleigh (Site #27) - Western Blvd Site 1-2, Raleigh (Site #28)

3.1.4 MOEs for Reliability Assessment

Probe-based data can provide aggregated speed and travel time for a certain period of time, which could support various performance assessment methods. The Highway Capacity Manual (HCM) indicates that the performance measurement is based on Planning Time Index (PTI), the 80^{th} Travel Time Index, the Mean Travel Time Index, the Misery Index, and Reliability Rating. The FHWA reliability performance measurement method, Level of Travel Time Reliability (LOTTR), was also applied to this study. Additional graphical analyzing methods such as Net Travel Time versus Interquartile Range (NTT/IQR) plot, Cumulative Distribution Function (CDF) of Travel Time, Congestion Stack diagram, and NPMRDS outputs were also used to better illustrate the changes of reliability. By analyzing travel time data aggregated over different periods of time, the reliability during peak hour, the changes of reliability under different months or different years could be revealed. In addition, weather-related reliabilities were analyzed by comparing the speed-time diagrams under different weather conditions. Since one of the research tasks is to test the reliability of probe data, this research used linear regression analysis to investigate the correlation between probe-based speed data and aggregated trajectory speed data.

3.2 Data Collection

Table 2 summarizes the candidate sites for each identified factor and data availability from each data source. It can be seen that for most of the sites, traffic performance data are available from multiple data sources, which could minimize the potential error caused by a single data source. The probe data that contain travel time and speed information can be acquired from the Regional Integrated Transportation Information System (RITIS) website. The NOAA weather station data under different weather categories will be obtained from NOAA website. For each weather category, speed data will be aggregated to daily average speed.

Table 2 - Sites Categorized in Use Cases and Data Resources

Impact Factor	**Data Source**				
	INRIX	**HERE.com**	**NPMRDS**	**I2D**	**NOAA**
Peaking Pattern	1	1	n/a	n/a	n/a
Seasonal Effects	2, 3, 4, 5	2, 3, 4, 5	n/a	n/a	n/a
ATM Strategies	6, 7, 8, 22	6, 7, 8, 22	n/a	n/a	n/a
Quantifying impacts of new development	9, 10	9, 10	9	n/a	n/a
Isolating effects of severe weather	n/a	n/a	n/a	n/a	11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24
Probe compared to High Resolution Vehicle Trajectories	25, 26, 27, 28	25, 26, 27, 28	n/a	25, 26, 27, 28	n/a

Note: Site number refers to Table 1.

3.3 Data Assessment

Table 3 details the methodologies used for assessing the impacts of each identified factor on arterial reliability. Most sites are analyzed by multiple methods, which aims at comparing the applicability of the selected method(s) for each impact factor. In practice, data analysis over a long time period (such as 4-hour or 8-hour) tends to smooth the impacts of the factors on travel time reliability, which cannot capture the most challenging situation. In this regard, this research analyzed only traffic performance data collected from workday AM and PM peak periods. Detailed descriptions of assessing data for different factor are presented at the following subsections.

Table 3 - Sites Categorized in Use Cases and Analyzing Methods

Impact Factor	**Reliability Assessment MOE**						
	TTI/IQR	**Average Travel Time**	**CDF of Travel Time**	**Reliability Analysis**	**Monthly Speed Percentile Stack Diagram**	**Corridor by Condition**	**Speed vs. Speed Comparison**
Peaking Pattern	1	1	1	n/a	n/a	n/a	n/a
Seasonal Effects	n/a	n/a	n/a	n/a	2, 3, 4, 5	n/a	n/a
ATM Strategies	n/a	6, 7, 8, 22	n/a	n/a	n/a	n/a	n/a
Quantifying impacts of new development	9	n/a	10	9, 10	n/a	n/a	n/a
Isolating effects of severe weather	n/a	n/a	n/a	11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24	n/a	11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24	n/a
Probe compared to High Resolution Vehicle Trajectories	n/a	n/a	n/a	n/a	n/a	n/a	25, 26, 27, 28

Note: arterial name refers to Table 1.

3.3.1 Peaking Patterns Over Time

The analyzed site is Western Boulevard in Raleigh, North Carolina. The peak period was defined from 6:00 to 9:00 for AM peak and 16:00 to 18:00 for PM peak. Both traffic directions of the arterial were selected. Figure 1 shows the location of the Western Boulevard case study arterial. The study area starts from Avent Ferry Rd to Method Rd with a length of 3 miles. For each direction, three TMC segments were observed on this arterial. Since the North Carolina State

University is located in the vicinity of this study arterial, it is expected that the seasonal commuting traffic will significantly impact the travel time reliability of the arterial.

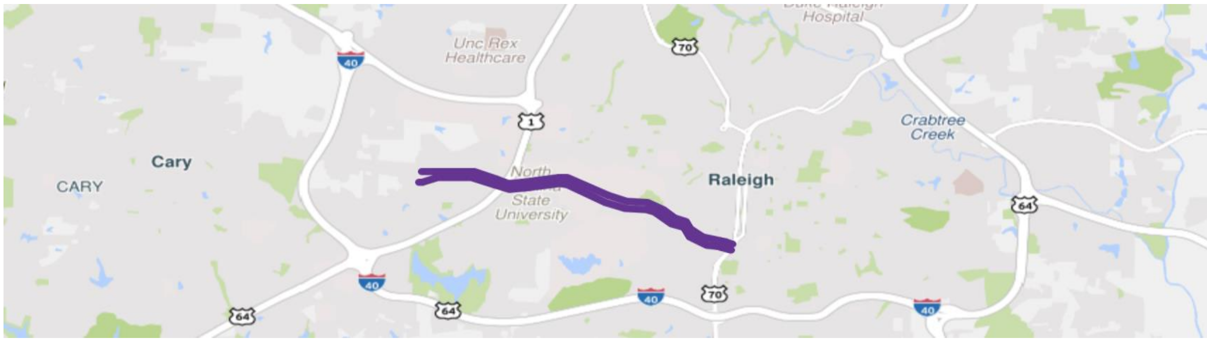

Figure 1 - Western Boulevard Case Study Arterial

The monthly AM and PM traffic performance data between 2016 and 2017 were prepared for data analysis. Figure 2 compares the average travel time during PM peak hours in 2017 when the University is in and out of session for the eastbound traffic. Overall, travel times in the Here.com dataset were significantly higher than those from INRIX. While the TMC segment definitions are nearly identical, it is possible that one data source includes speeds from turning movements or filters out low speed readings differently. However, both Here.com and INRIX datasets indicate a significant impact to peak hour traffic due to the schedule of the University. To further reveal the impact of seasonal commuting traffic on travel time, a cumulative distribution function diagram of travel time was plotted, as illustrated in Figure 3. Similarly, results show that travel time in no-school season was lower than travel time in school season.

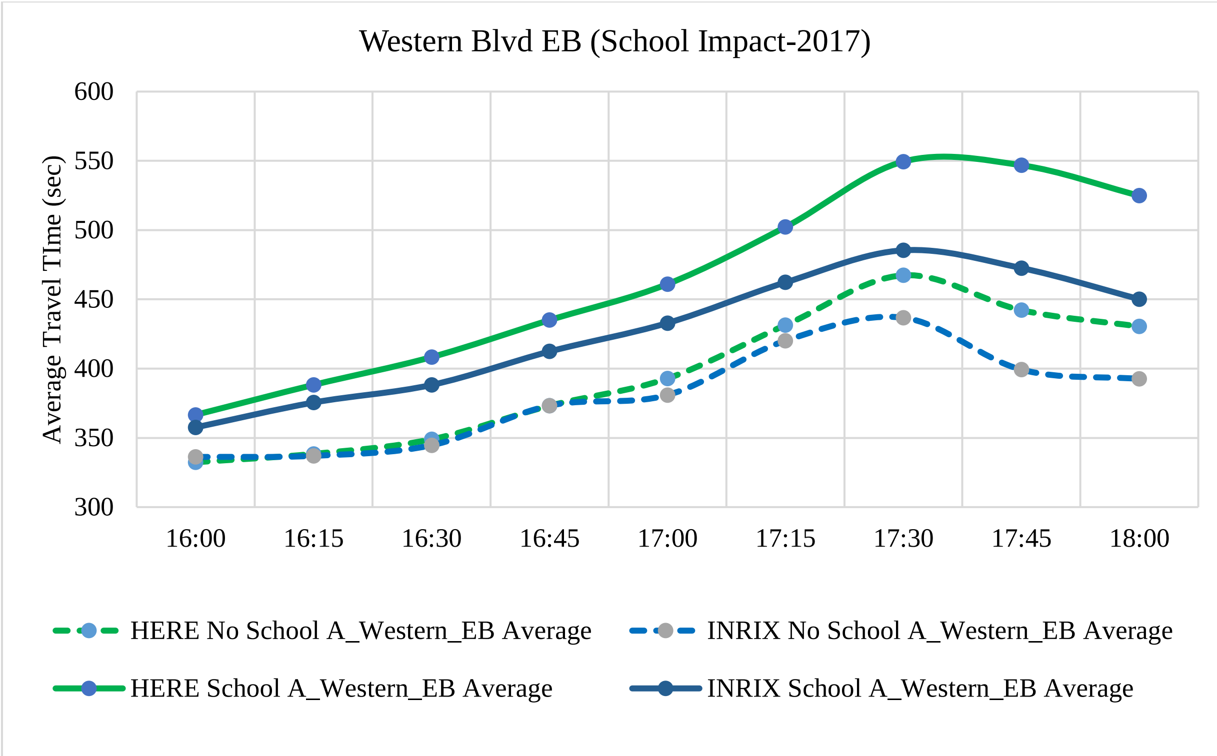

Figure 2 - 2017 PM Travel Time Comparison

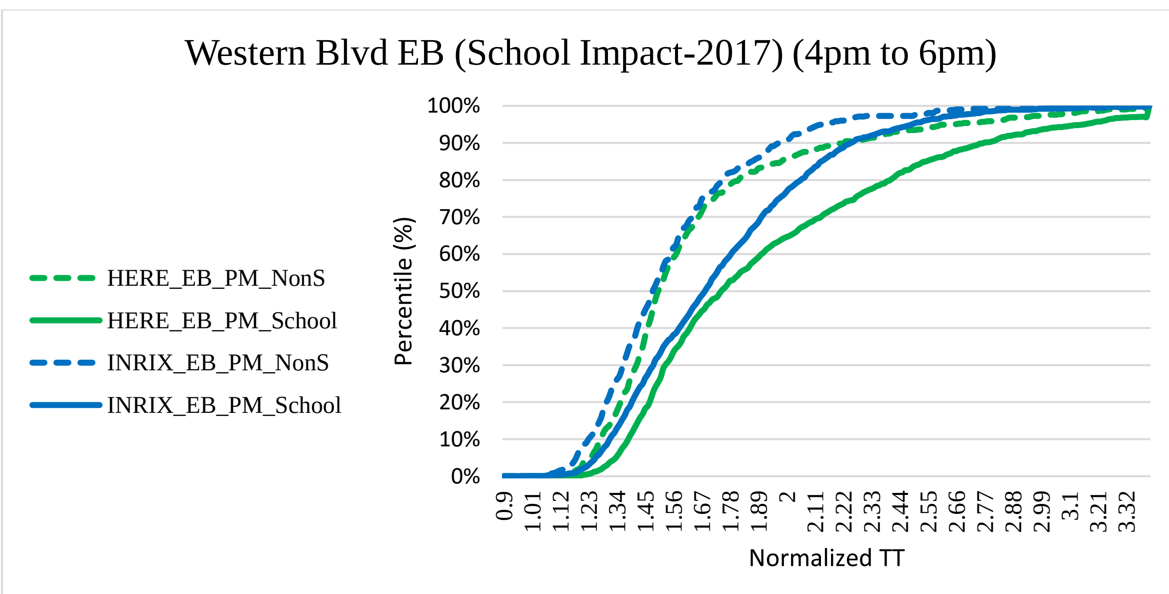

Figure 3 - CDF of 2017 PM Travel Time Comparison

Table 4 shows the numerical comparisons of percentile travel time in 2017 between different data sources. It was found that in general, school season has a higher travel time compared to non-school season; on average, travel time in school season is 18 percent higher than non-school season when using HERE.com dataset (12 percent higher when using INRIX dataset). The impact of school season on travel time reached its peak when using the 80th percentile travel time data, which was 33 percent.

Table 4 – Reliability Analysis Result

Data Source	Impact Factor	Travel Time (min)				
		Average	**95th**	**80th**	**50th**	**LOTTR**
Here.com	No School Season	1.65	2.62	1.81	1.50	1.21
	School Season	1.94	3.16	2.41	1.75	1.38
	School Impact (%)	**18%**	**20%**	**33%**	**16%**	**14%**
INRIX	No School Season	1.55	2.13	1.75	1.48	1.18
	School Season	1.74	2.49	2.05	1.68	1.22
	School Impact (%)	**12%**	**17%**	**17%**	**14%**	**3%**

Note: LOTTR refers to Level of Travel Time Reliability.

In addition, Figures 4 and 5 were plotted to illustrate year-level reliabilities. Both figures show monthly average travel time index within the year as well as the standard deviation of the index. For Eastbound traffic, AM peak hour travel time data (upper Figure 4) from two different sources are close with a small standard deviation. PM peak hour travel time data (lower Figure 4) show that both the travel time and the variability increased. In addition, it was found that school season months (i.e., the highlighted areas in Figure 4) usually have larger travel time and standard deviation of TTI than no school months. The same trend is also observed from the Westbound traffic, as illustrated in Figure 5. This indicates that for the Western Blvd arterial, travel time reliability of school season is lower than no school season, which is mainly due to the increased traffic demand during school season; in addition, for both traffic directions, travel time reliability under PM peak period tends to be lower than AM peak period.

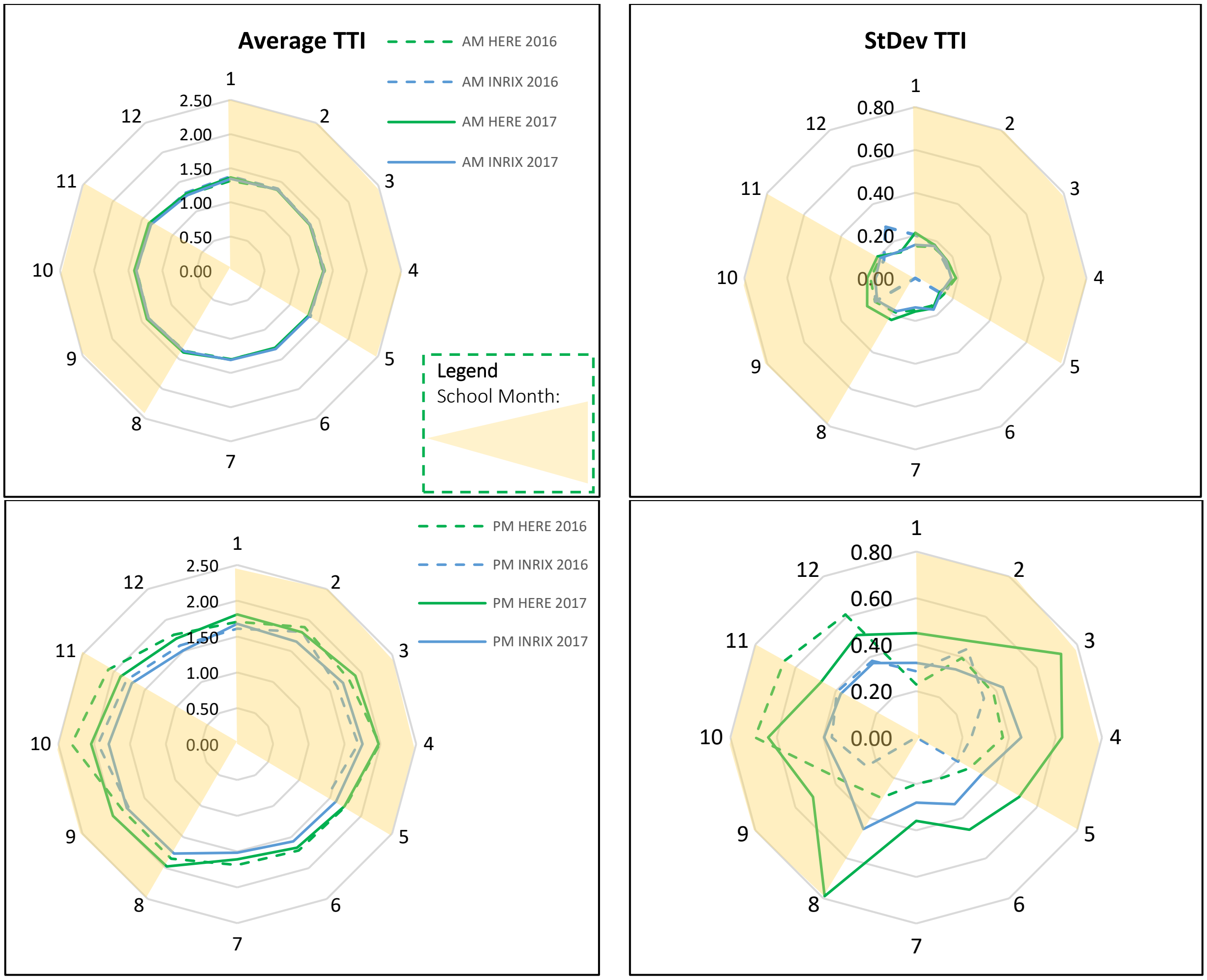

Figure 4 - Monthly Breakdown of Average TTI and StDev TTI for Eastbound Traffic

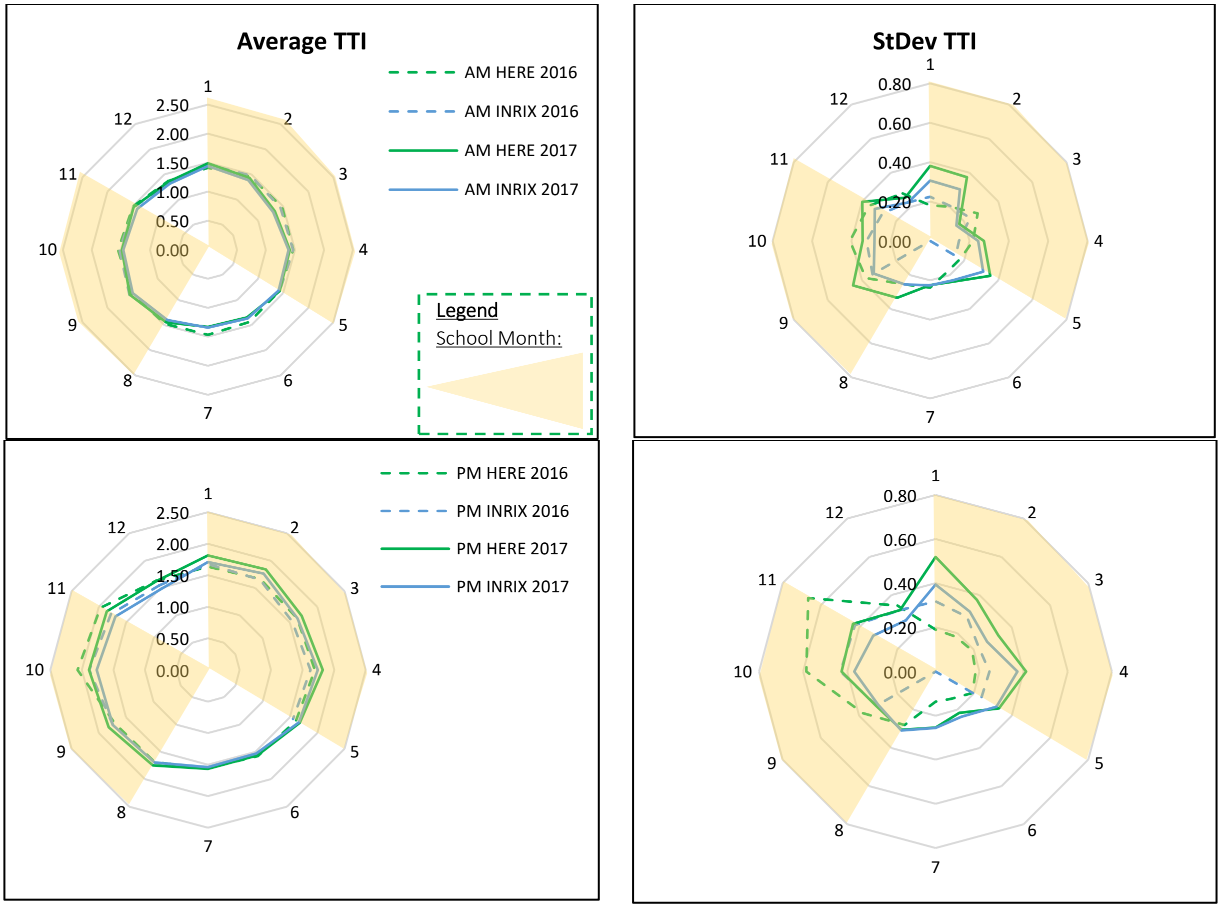

Figure 5 - Monthly Breakdown of Average TTI and StDev TTI for WB

After analyzing monthly travel time reliability data, the yearly data is analyzed to reveal the macroscopic trend of travel time reliability. Figure 6 shows the annual AM and PM IQR plot from 2010 to 2018 based on INRIX data, and from 2015 to 2018 based on Here.com data. The plots depict the historical trend of the study arterial. In addition, it was also found that the INRIX data had a significant shift between 2013 and 2014. Potential causes include traffic growth in the area as well as significant diversion possible from the parallel Hillsborough St corridor which had a reduction in lanes during this period.

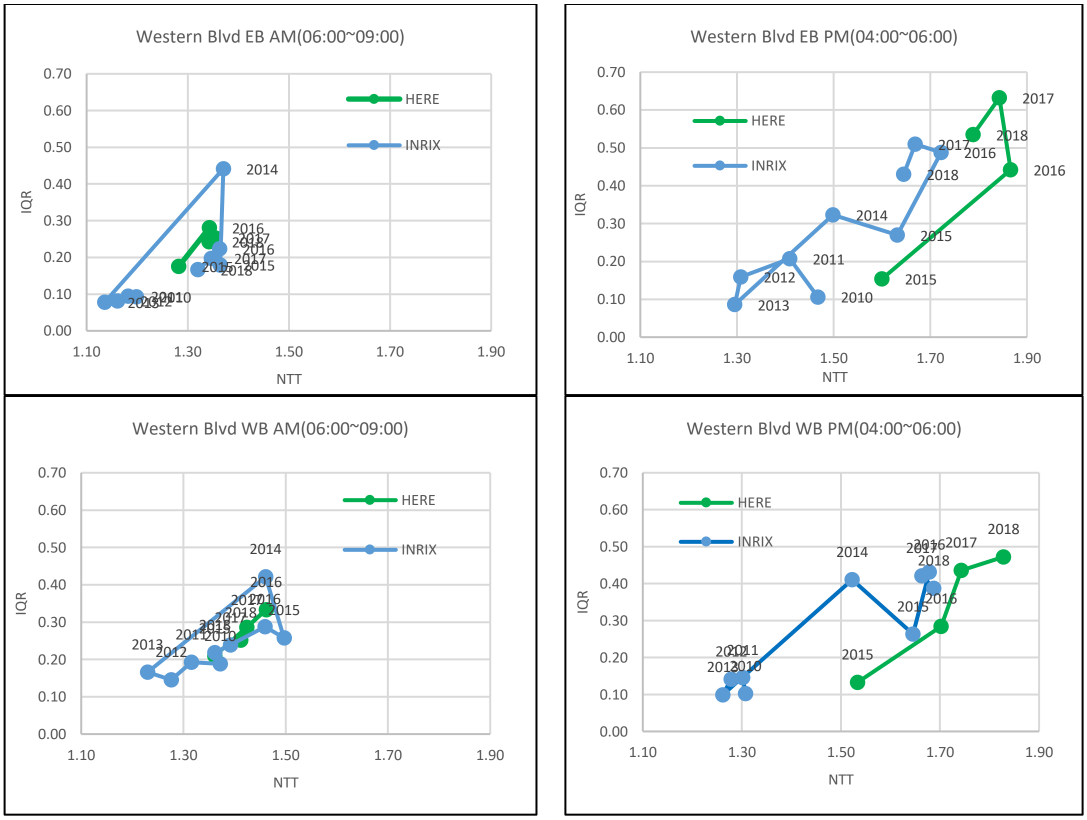

Figure 6 - IQR Analysis for AM and PM Yearly Data from INRIX and HERE.com

3.3.2 Seasonal Tourism Traffic Effects

The sites used for evaluating seasonal effects are located in Cherokee, Asheville, and Wilmington. For the Wilmington site, AM & PM speed data during both weekdays and weekends were analyzed to capture the impact seasonal effects on travel time reliability. The peak time was also defined as 6:00 to 9:00 and 16:00 to 18:00 for AM and PM peaks, respectively. For the other sites, traffic performance data during weekdays were analyzed only. For most sites, traffic performance data are available from 2016 to 2017 and speed data were aggregated to 15-minute average speed. Some of the sites used 2015 and 2016 data for comparison because the traffic message channels (TMCs on those sites were not available in 2017. Figure 7 shows the US 19 arterial located in Cherokee, North Carolina. It contains 6 TMCs for each direction and the length of the arterial is 17 miles. Figure 9 illustrates the US 441 arterial located in Cherokee, North Carolina. It contains 5 TMCs each direction and the length of the arterial is 10 miles. This arterial passes through the downtown Cherokee and connects Cherokee to the Great Smoky Mountains National Park.

To better reveal the seasonal impact on arterial reliability, the percentile speed stack diagrams were created. Figure 8 and Figure 10 show the example percentile speed diagram for US 19 Southbound and US 441 Southbound based on both INRIX and HERE.com Data. In both figures, the vertical-axis is the name of each intersected street and TMC; the horizontal-axis is the month of the year. Of these graphs, only the US 441 sections shows significant seasonality with more congestion (more orange region) in 2016 and 2017. Figure 11 presents the legend of the speed percentile stack diagram, where Green color means a higher speed and Red color represents a lower speed. The larger the color block is, the more percentages of the represented speed exist in the specific month. In addition, the black blocks mean there is no available data from the TMC in those months.

Figure 7 – US 19 Cherokee Route

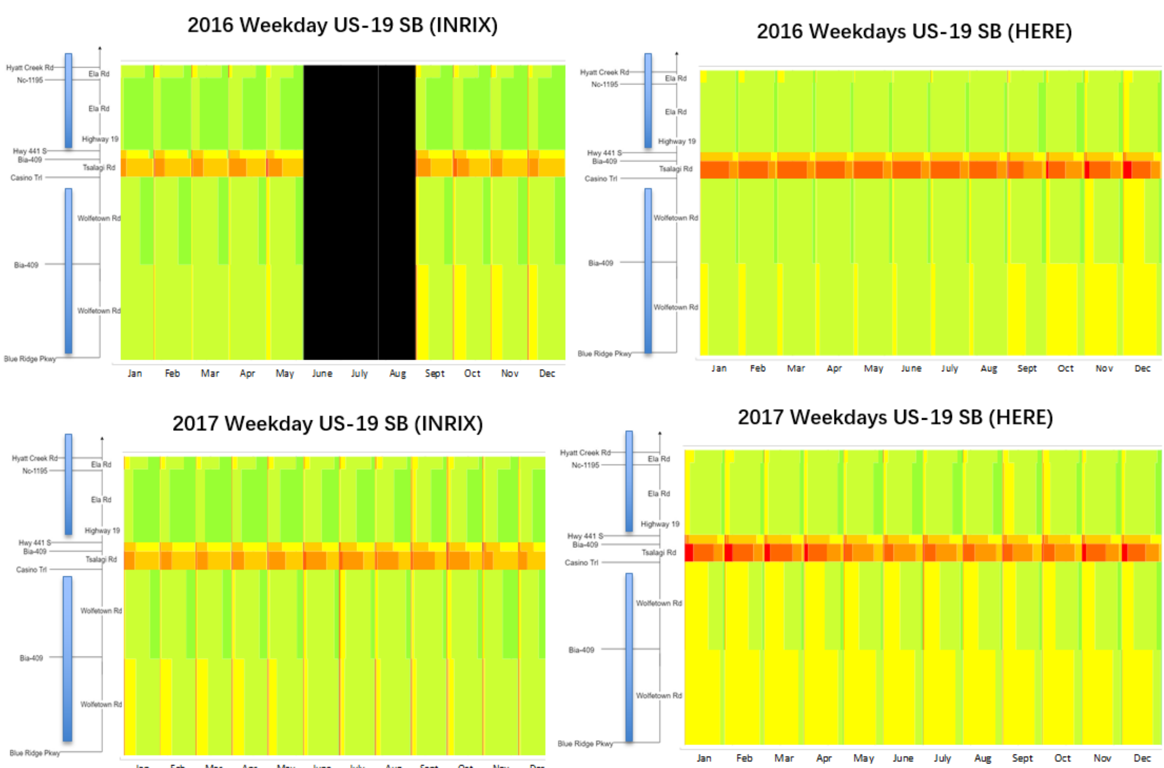

Figure 8 - US 19 SB Here. com Speed Percentile Stack Diagram

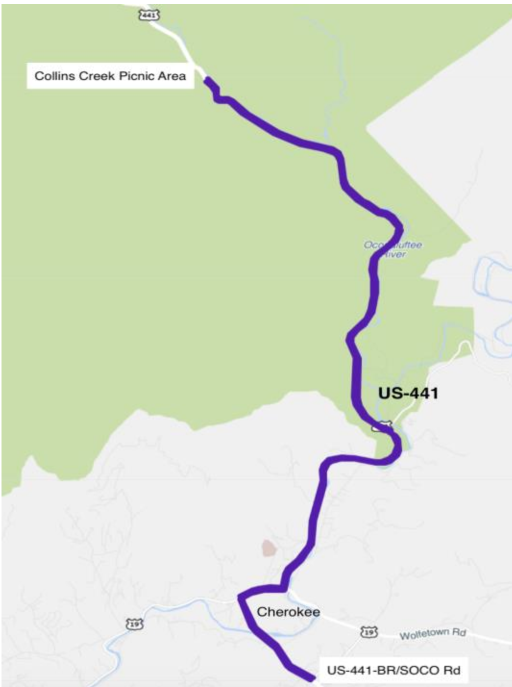

Figure 9 – US 441 Route

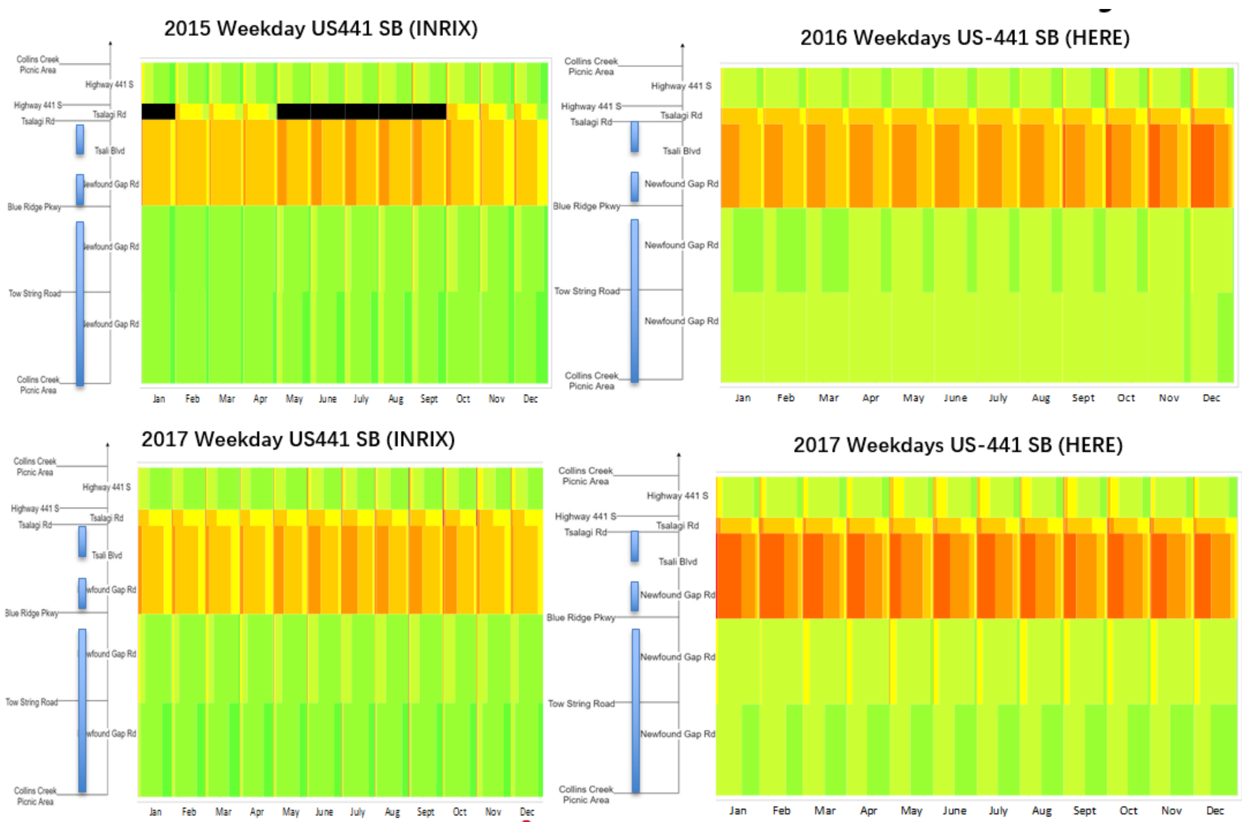

Figure 10 – US 441 SB INRIX Data Speed Percentile Stack Diagram

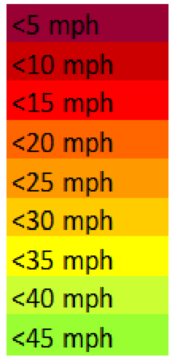

Figure 11 - Speed Percentile Stack Diagram Legend

Results reveal that the speed distribution shows a significant deterioration after September 2016. This pattern can also be observed at other sites. One possible reason is Here.com changed the algorithm for speed measurement in September 2016. Therefore, due to the unexplained shift problem, INRIX data tends to be more sensitive to the seasonal changes of traffic demand.

3.3.3 ATM Strategy

The four sites selected for analyzing the impact of ATM strategies on travel time reliability are located in Raleigh. Leesville Road arterial is from Norwood Road to Fairbanks Drive. The Creedmoor Road route is from Norwood Road to Strickland Road. The Six Forks Road route is from Durant Road to Strickland road. Falls of Neuse Road route is from Durant Road to Strickland Road. Figure 12 illustrates the origin and destination of the four sites.

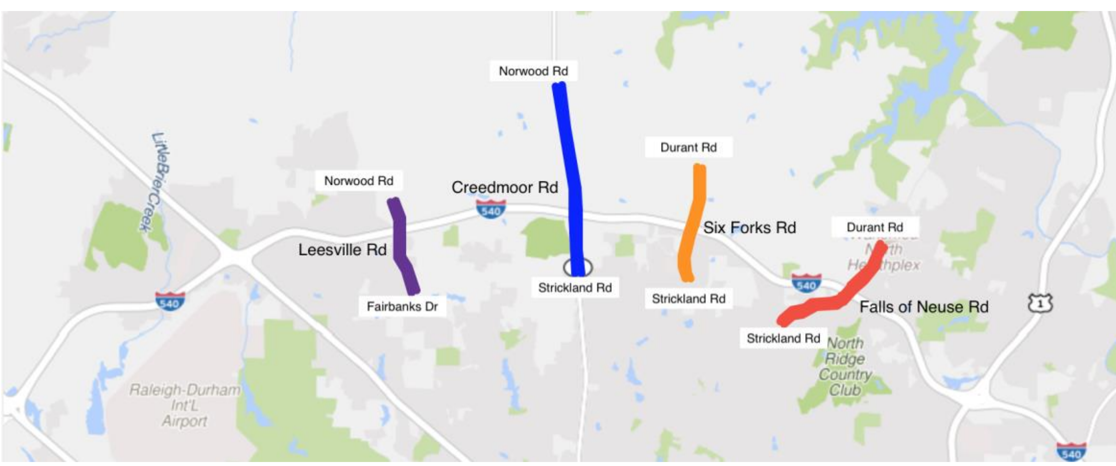

Figure 12 - ATM Strategies Analyzing Sites

The ATM strategy problem analyzed by this research is the potential spill-back effects onto arterials from freeway on-ramp metering, which was applied at 4 ramps at I-540 westbound in September 2017. The ramp meters located on the on-ramp near the freeway gore queue traffic during the AM peak and do include queue detectors at the top of the ramp, however there is still concern that the strategy may negatively impact adjacent arterials. After a one-month adaptation period, it was assumed that drivers have adapted their behavior to ramp metering from October 2017. The deployment of the ramp meters, including construction and initial testing, may have influenced driver route decisions so a burn-in period was established for the traffic responsive comparison as well (i.e., until February 2018). Therefore, the majority of comparisons applied to traffic data collected between October 2016 and October 2017 and between February 2017 and February 2018.

Table 5 below documents the reliability analysis outputs. The 95th percentile travel time has the most significant change compared to 80th percentile and 50th percentile travel time data. Both Here.com and INRIX data show the same pattern. Figure 13 presents the AM Average Travel time distribution for Falls of Neuse Southbound traffic. Results show that in general, travel time decreased after the implementation of ATM strategy. Figure 14 compares the impacts of two different ramp metering control methods (i.e., fixed time metering strategy and traffic responsive metering strategy) on arterial reliability. It was found that travel time under ramp metering control has a smaller variability and the maximum travel time (i.e., the worst case) also decreased in comparison with no ramp metering control. A shift of peak period is also observed from the Here.com data; both comparisons indicate an earlier peak travel time which may indicate peak spreading due to the presence of ramp meters. This shift is more pronounced in the traffic responsive period with a 30 minute earlier peak 15-minute travel time.

Table 5 – Travel Time Index (TTI) Reliability Analysis Output for ATM Strategy Sites

Scenario	Route	Here.com			INRIX		
		95th	80th	50th	95th	80th	50th
Impact of Traffic fixed Rate Ramp Meters (Opening Day Impact)	A_Leesville_NB	-3%	-1%	0%	4%	0%	0%
	A_Leesville_SB	-4%	-1%	1%	-4%	-4%	2%
	B_Creedmoor_NB	0%	2%	-1%	-1%	2%	3%
	B_Creedmoor_SB	-4%	2%	2%	-7%	-1%	-2%
	C_Six Forks_NB	-2%	0%	2%	-3%	-2%	-2%
	C_Six Forks_SB	-7%	-4%	0%	-3%	-3%	-3%
	D_Falls of Neuse_NB	1%	2%	4%	2%	1%	1%
	D_Falls of Neuse_SB	-13%	-13%	-33%	-7%	-8%	-4%
Impact of Traffic Responsive Ramp Meters (Longer Term Impact)	A_Leesville_NB	-5%	-3%	-4%	-4%	-2%	0%
	A_Leesville_SB	-3%	-3%	0%	1%	0%	1%
	B_Creedmoor_NB	4%	2%	0%	1%	4%	5%
	B_Creedmoor_SB	-7%	0%	1%	-13%	-7%	-2%
	C_Six Forks_NB	1%	1%	1%	-6%	-2%	0%
	C_Six Forks_SB	-13%	-8%	-7%	-14%	-8%	-2%
	D_Falls of Neuse_NB	2%	-3%	-3%	-2%	0%	-1%
	D_Falls of Neuse_SB	-9%	2%	2%	-12%	-6%	1%

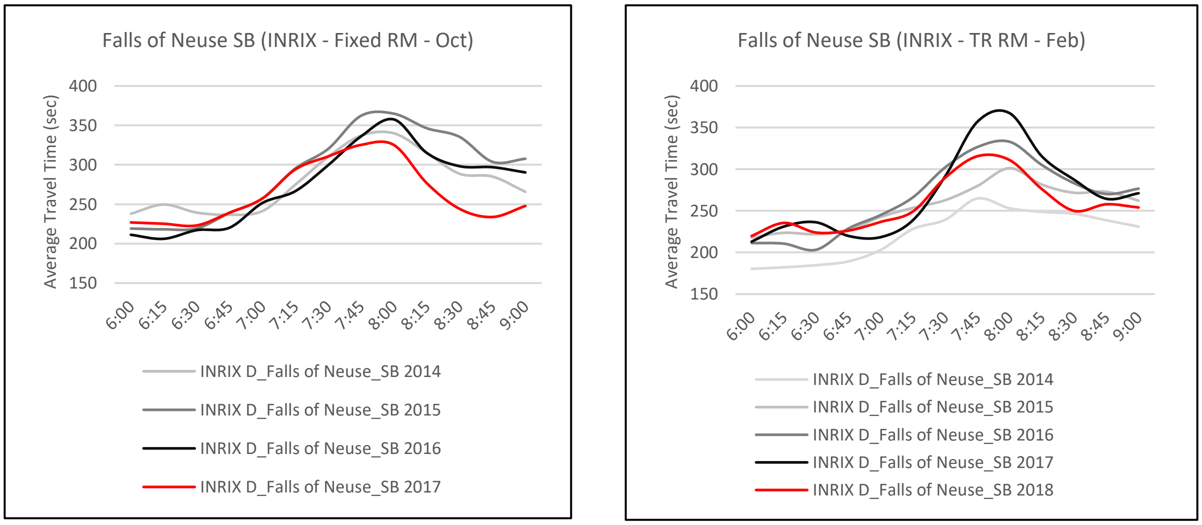

Figure 13 - Average Travel Time for AM Peak in Falls of Neuse Southbound

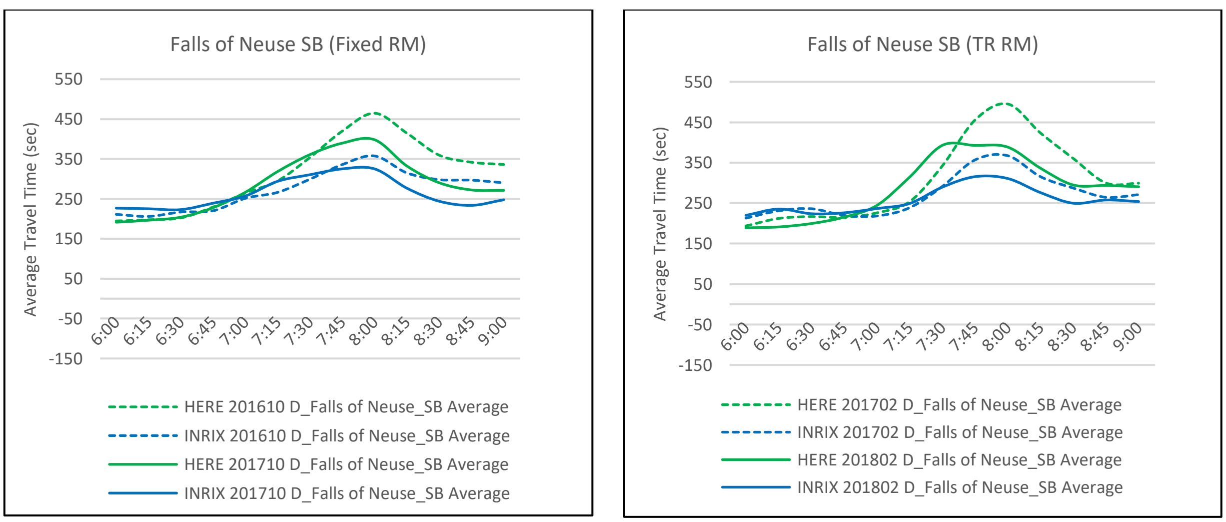

Figure 14 - Data Comparison of Different Ramp Meter Control

Overall, ramp metering strategies, which were found to significantly improve freeway operation in previous NCDOT research *(30)*, do not have clear negative impacts to the reliability of the arterial that connects to the freeway. Maximum arterial travel times were found to be lower after implementation of the ramp meters and the peak period began earlier in the morning. Count and origin-destination data would clarify if this was due to diversion or peak spreading of demand, but this data was not available for the study.

3.3.4 New Development

There are two sites used to analyze the influence of new developments on arterial reliability. The first site is US 64 at Apex, North Carolina, where a new Costco shopping center opened in March 2016 at a business plaza in the vicinity of US 64. In addition to this shopping center, the plaza has been continuously developing since May 2016 with various firms start their business. The new development of the plaza is considered contributing to the trip generation and attraction on US 64. Therefore, by analyzing the changes of travel time on US 64, it is expected that the impact of new development on arterial reliability could be revealed.

Table 6 - Reliability Analysis for PM US 64 Route

AM (INRIX)	EB			WB		
	2016	2017	% Change	2016	2017	% Change
95th	2.07	1.94	-6%	1.47	1.41	-4%
80th	1.61	1.48	-8%	1.37	1.30	-5%
50th	1.22	1.18	-3%	1.27	1.22	-4%

AM (Here.com)	EB			WB		
	2016	2017	% Change	2016	2017	% Change
95th	2.00	2.11	6%	1.51	1.46	-3%
80th	1.57	1.58	1%	1.44	1.38	-4%
50th	1.30	1.23	-5%	1.32	1.27	-4%

AM (Here.com)	EB			WB		
	2016	2017	% Change	2016	2017	% Change
95th	2.00	2.11	6%	1.51	1.46	-3%
80th	1.57	1.58	1%	1.44	1.38	-4%
50th	1.30	1.23	-5%	1.32	1.27	-4%

PM (Here.com)	EB			WB		
	2016	2017	% Change	2016	2017	% Change
95th	2.32	2.58	11%	2.05	2.44	19%
80th	1.83	1.99	9%	1.73	1.98	14%
50th	1.49	1.51	2%	1.48	1.53	3%

Table 6 presents the numerical result of reliability analysis. Note that since the INRIX databased does not contain summer 2016 data and considering the Costco opened in 2016, some of the 2016 data will also be impacted. Therefore, the significance of the change might be weakened. Figure 15 and Figure 16 compare the Monthly trend of NTT/IQR based on INRIX data and Here.com data. NPMRDS, as a tool to assess the data availability, is also used. Figure 17 shows the result from NPMRDS. Both probe sources showed increases in typical travel time and worsening reliability for the PM periods in both directions which can be attributed to additional traffic due to development, however the AM period is mainly unchanged or improved likely due to the signal retiming performed.

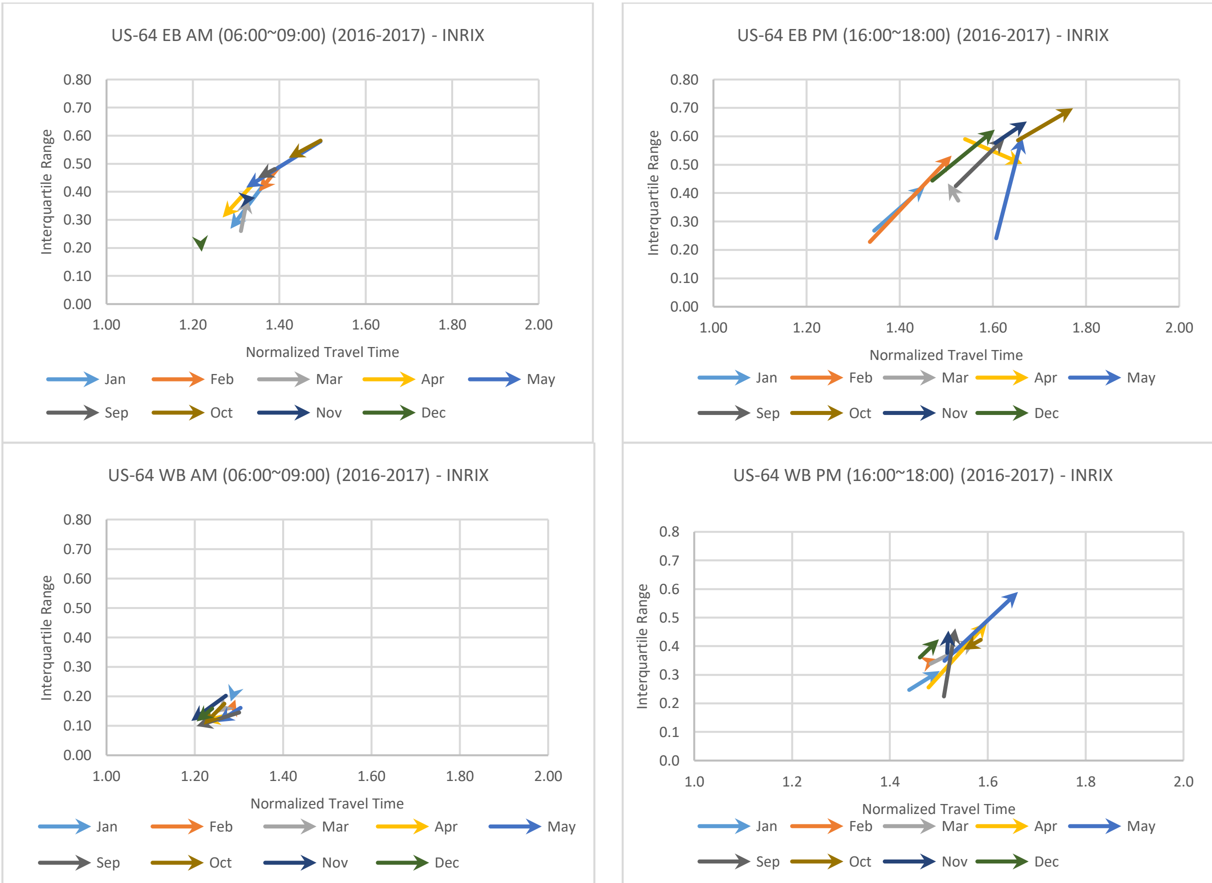

Figure 15 - INRIX Monthly Trend NTT/IQR Comparison

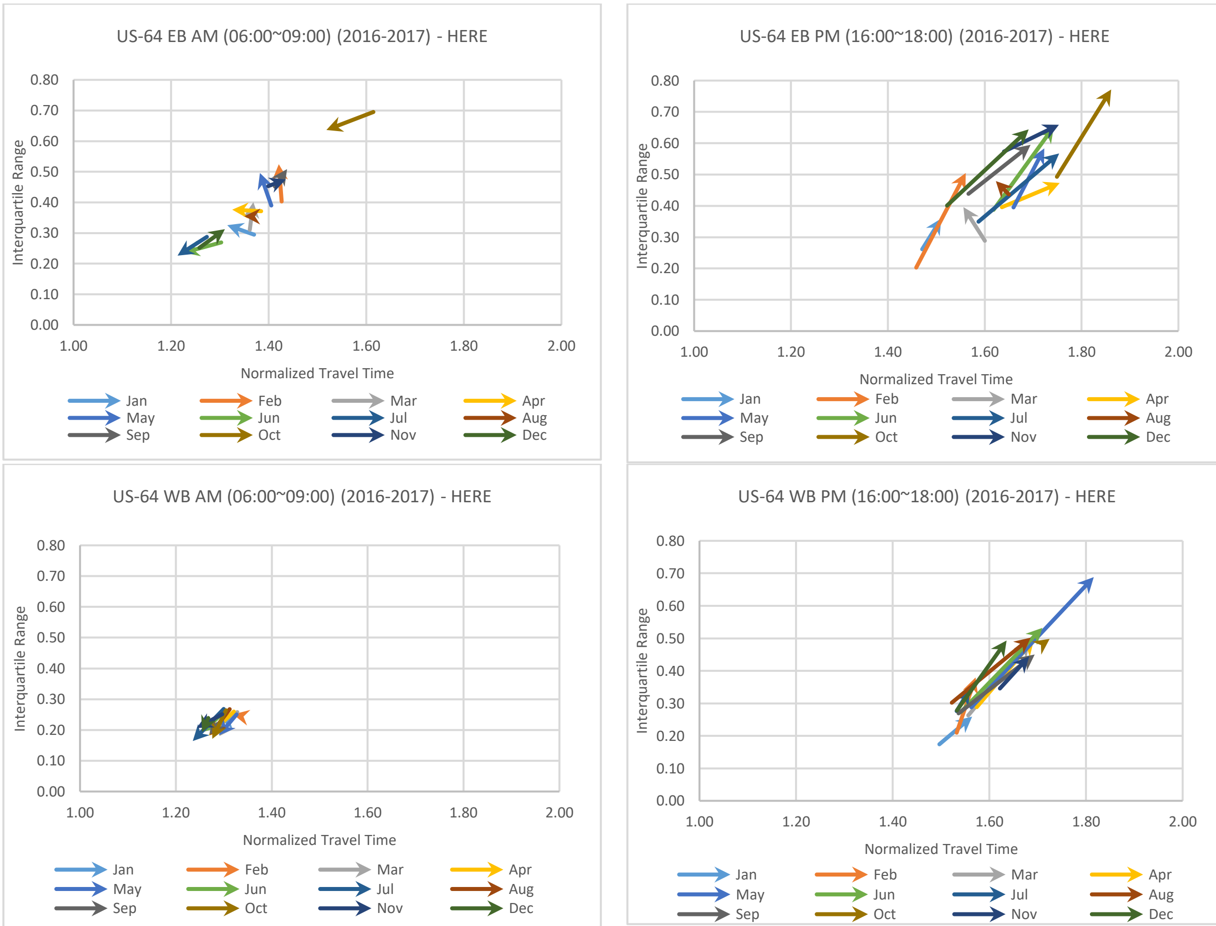

Figure 16 - Here.com Monthly Trend NTT/IQR Comparison

The second site is a three-mile section of US 70 Business located in Smithfield, North Carolina. The analysis period contains AM Peak, Mid-day and PM Peak. The AM period is defined from 6 am to 10 am. The Mid Day period is defined from 11 am to 3 pm. The PM period is defined from 4 pm to 8 pm. This study used both graphical and numerical methods to analyze the reliability. The analysis results are shown in Figure 18 and Table 7. One critical observation is the step functions of the CDFs which indicate clusters of travel time associated with the number of stops at signals on the corridor. The travel times in the tail most likely relate to two or more stops which could be addressed by better signal coordination.

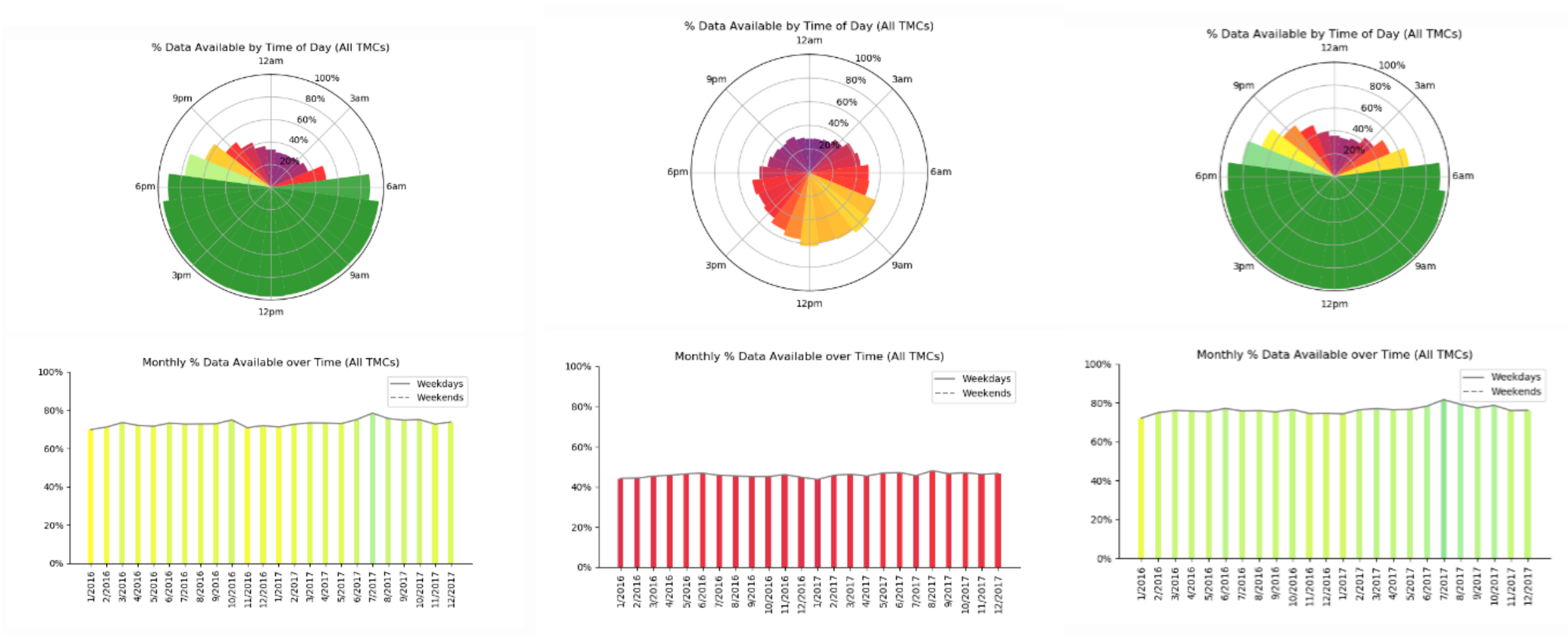

Figure 17 - NPMRDS Analysis Result

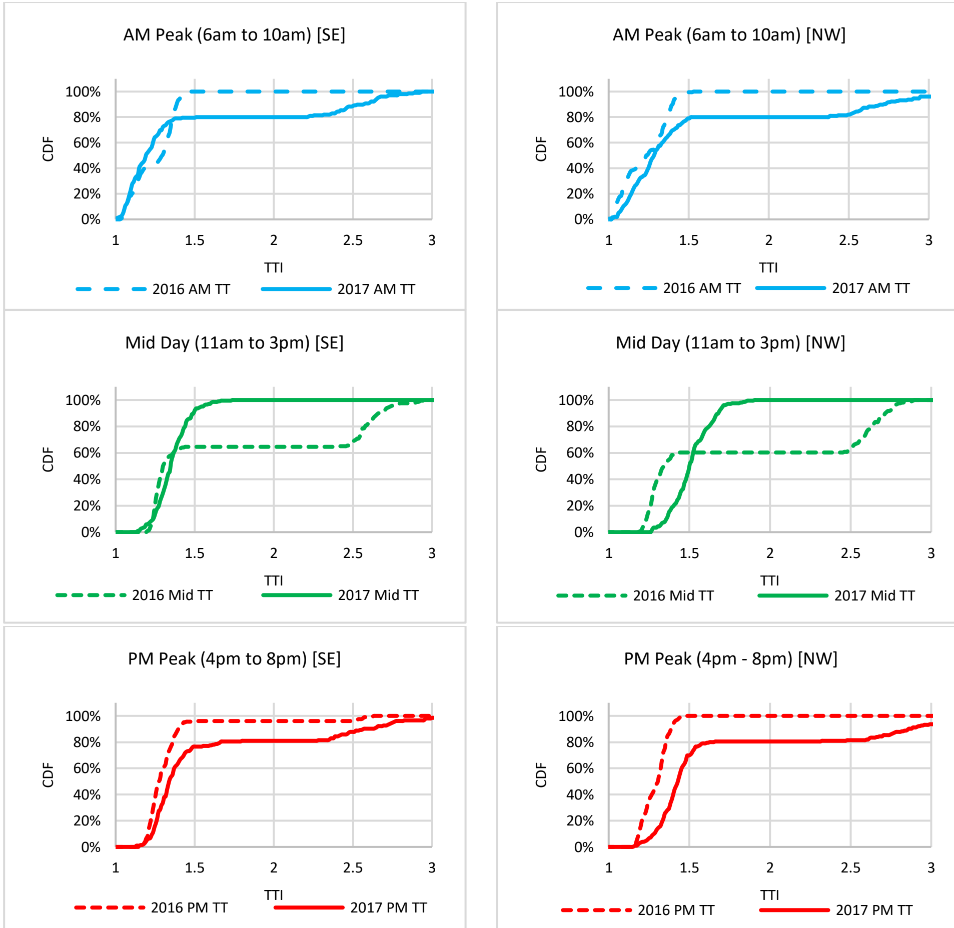

Figure 18 - CDF of Travel Time in US 70 Business

Table 7 - Numberical Comparison Result in US 70 Business

SE Direction Key Reliability PMs				NW Direction Key Reliability PMs			
	50th	**80th**	**LOTTR**		**50th**	**80th**	**LOTTR**
2016 AM TT	1.30	1.37	1.05	**2016 AM TT**	1.23	1.37	1.11
2017 AM TT	1.19	1.51	1.26	**2017 AM TT**	1.29	1.51	1.18
% change	-8.1%	10.3%	20.0%	**% change**	4.2%	10.1%	5.7%
2016 Mid TT	1.31	2.58	1.97	**2016 Mid TT**	1.35	2.64	1.96
2017 Mid TT	1.35	1.44	1.06	**2017 Mid TT**	1.50	1.63	1.08
% change	3.4%	-44.2%	-46.0%	**% change**	11.6%	-38.5%	-44.9%
2016 PM TT	1.28	1.37	1.07	**2016 PM TT**	1.31	1.36	1.03
2017 PM TT	1.34	1.67	1.24	**2017 PM TT**	1.43	1.63	1.13
% change	4.8%	21.8%	16.2%	**% change**	9.3%	19.9%	9.7%

The result does not show a significant trend of improvement or weakening. For instance, when using the 50th percentile travel time index for comparison, it was found that the development slightly deteriorated travel time reliability. While when comparing the 80th percentile travel time index data, result show that the new development resulted in adverse impacts on AM and PM travel time reliability but significantly improved Mid-day reliability.

In summary, from US 64 case study, the arterial signals coordination played an important role in reducing travel time and travel time variability during the AM peak despite development and traffic growth. Also, the INRIX and Here data are found have different results in terms of the amount of travel time reliability changes. For the US 70 Business site, the results show that signal retiming could have a considerable impact on travel time reliability. However, signal re-timing or other potential reliability impacting factors may alter and bias observations.

3.3.5 Severe Weather

There are 15 sites selected for analyzing the isolating effects of severe weather on travel time reliability. In Asheville, US 25 (north of I-240 Beltline), US 25 (Inside I-240 Beltline), US 70 / Tunnel Road East of Asheville, and NC 191 South of Asheville were selected. College Road, Military Cutoff Road and US 17 were selected as the routes in Wilmington. Charlotte contains four sites which are N. Graham Street, NC 16 Brookshire (North), NC 16 Brookshire (South) and Tryon Road. The final site was Capital Boulevard near I-440 in Raleigh. Based on NOAA dataset, each speed data point is assigned a weather condition. This research first plotted the speed profile under normal weather condition (i.e., baseline scenario); then, for each weather condition, a speed profile was plotted and compared to the baseline scenario. Figure 19 to Figure 22 illustrate the comparison results for four of the identified sites with the top section showing travel times and the bottom sections showing segment speeds. In addition, Table 8 numerically compares the differences in travel time reliability between clear weather condition and various adverse weather conditions in PM period in aggregate across all sites.

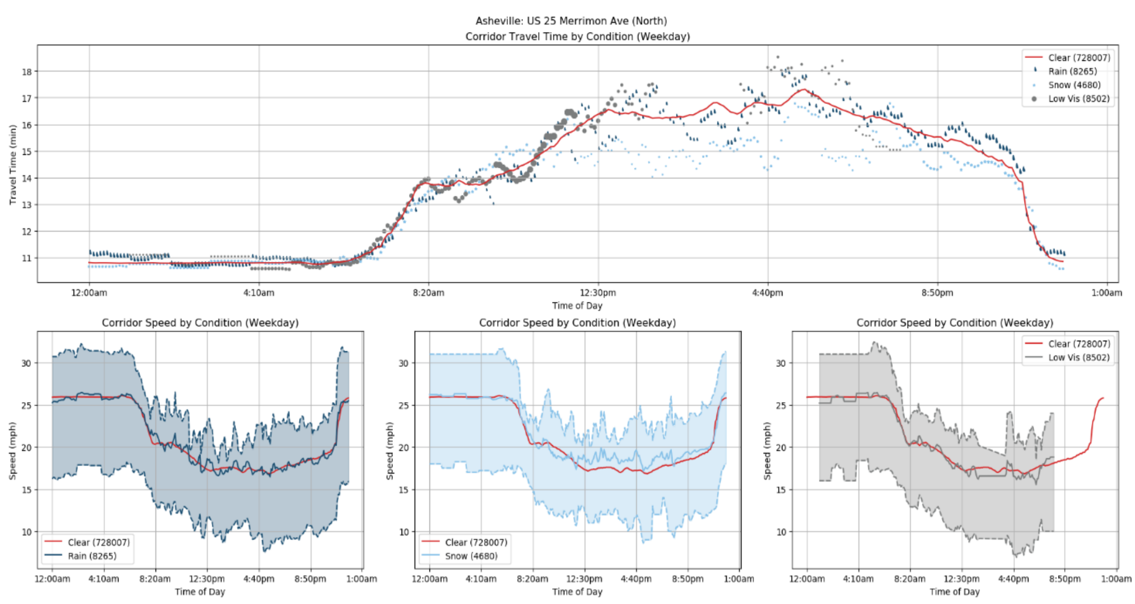

Figure 19 - Weather Impact Analysis Outputs for US 25

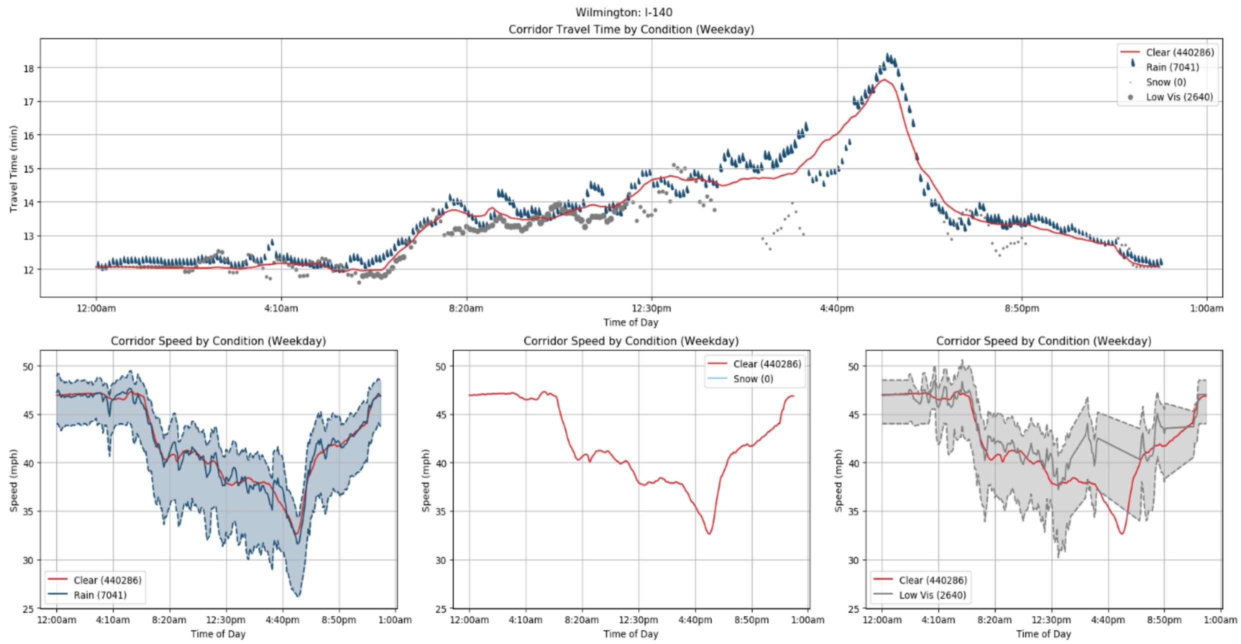

Figure 20 - Weather Impact Analysis Outputs for I-140

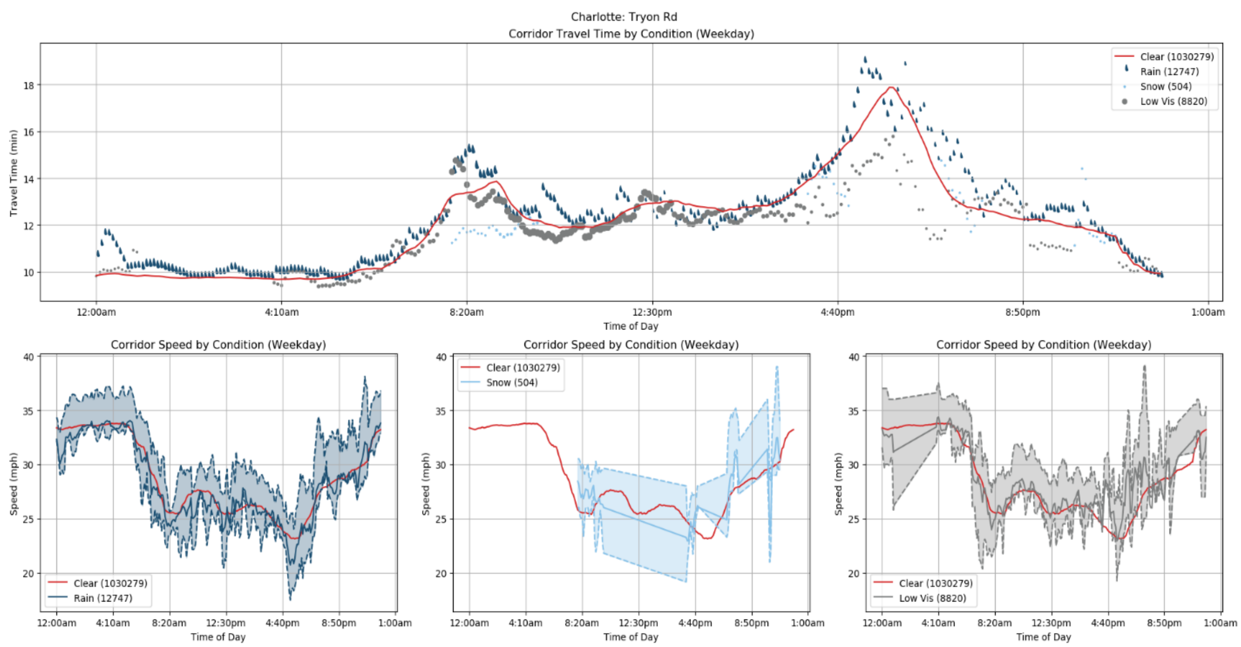

Figure 21 - Weather Impact Analysis Outputs for Tryon Rd

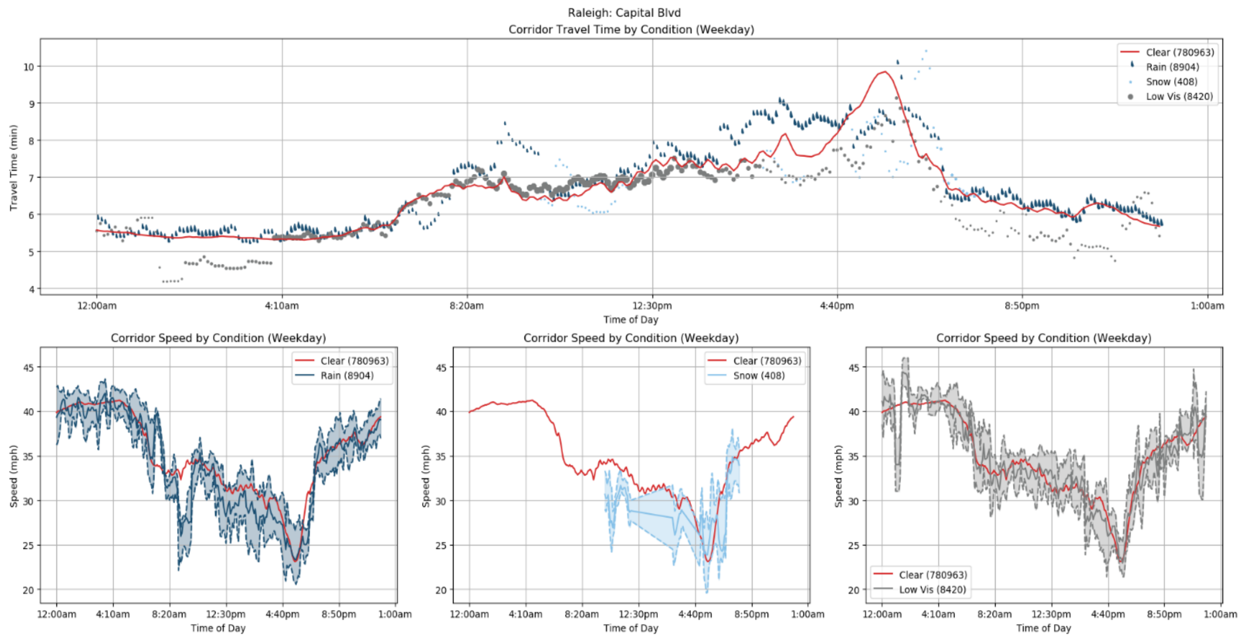

Figure 22 - Weather Impact Analysis Outputs for Capital Boulevard

Table 8 – Travel Reliability Comparison between Special Weather Condition and Clear Weather Condition based on all sites PM data

Reliability Data	% Change in Key Reliability Compared to Clear Weather Condition		
	Rain	Snow	Low Visibility
95th TTI	0.9%	-6.1%	-2.2%
80th TTI	3.0%	2.7%	1.8%
50th TTI	2.2%	6.3%	4.1%

Results revealed that snow weather has the most significant overall impact on arterial reliability. Prior research in the HCM identified different sections of TTI cumulative curve are impacted differently by different weather conditions. Nevertheless, it is necessary to point out that adverse weather events have the potential of changing traffic demand on the arterials, thus the presented comparison results may not exactly reflect the actual impacts of adverse weather on arterial reliability.

3.3.6 Probe-based Data Compared to High Resolution Vehicle Trajectories

To compare the travel time reliability generated by probe data and high-resolution vehicle trajectory data, it is necessary to have the same trajectory-level traffic performance data collected from both data sources. Table 9 provides the detailed number of drivers and number of trips in the i2D data during 2014 to 2017. The high-resolution trajectory dataset is proved to have sufficient amount to compare with probe dataset, and the comparison is only done where data from both sources are available. Figure 23 shows the location of the related sites that shown in Table 9.

Table 9 - Available Drivers and Trips for selected Sites

Route Name	# of Drivers				# of Trips			
	2014	2015	2016	2017	2014	2015	2016	2017
Avent Ferry Rd EB – Site 25	10	9	5	2	89	41	7	2
Avent Ferry Rd WB – Site 25	13	10	8	3	122	47	21	4
Glenwood Ave WB – Site 26	12	13	9	6	36	172	58	9
Tryon Rd EB – Site 27-1	9	11	4	3	27	68	10	5
Tryon Rd EB – Site 27-2	16	18	12	9	275	262	98	56
Tryon Rd EB – Site 27-3	8	10	6	4	37	61	42	16
Tryon Rd EB – Site 27-4	9	10	1	1	23	33	1	1
Tryon Rd WB – Site 27-1	8	8	2	1	27	28	2	1
Tryon Rd WB – Site 27-2	9	9	8	6	19	55	37	17
Tryon Rd WB – Site 27-3	18	14	13	13	298	270	110	61
Tryon Rd WB – Site 27-4	8	12	6	7	22	67	13	8
Western Blvd EB – Site 28-1	16	20	11	9	142	188	57	36
Western Blvd EB – Site 28-2	19	18	15	19	556	161	105	61
Western Blvd WB – Site 28-1	5	20	11	12	7	216	32	23
Western Blvd WB – Site 28-2	21	22	14	16	534	447	100	54

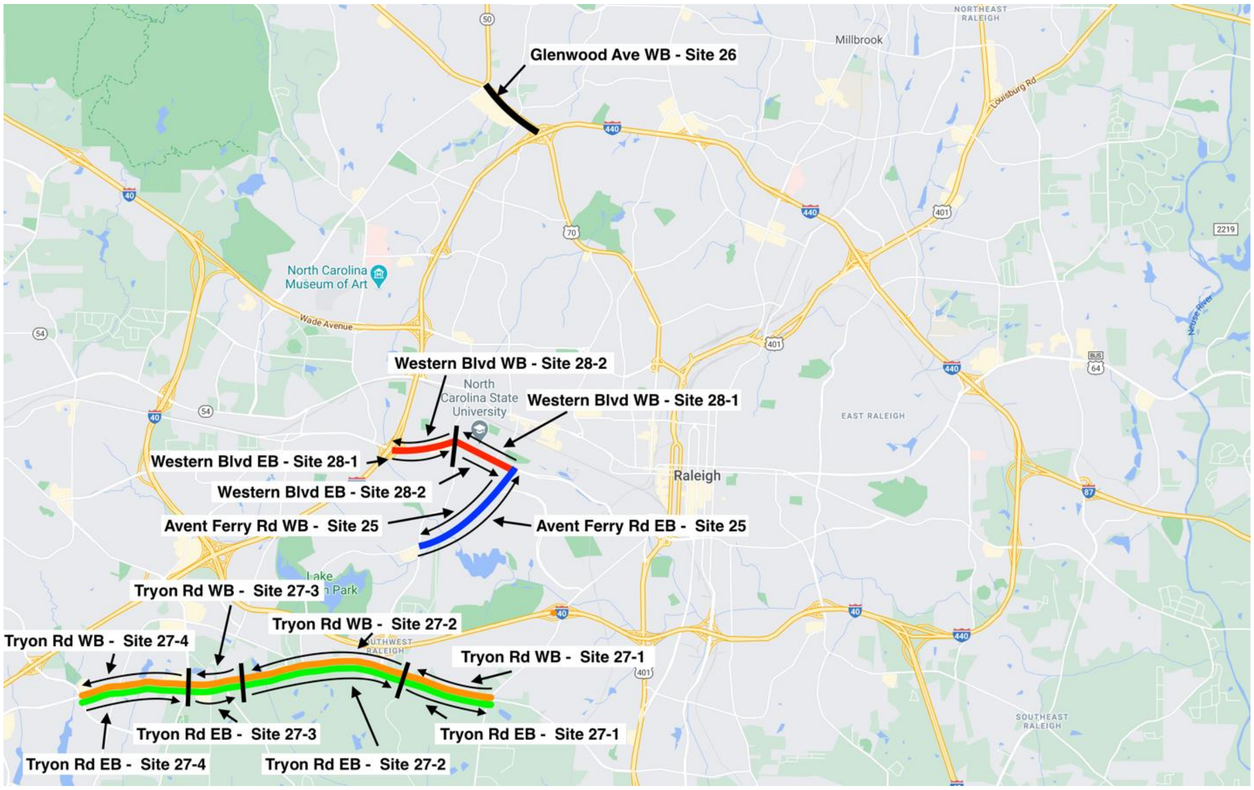

Figure 23 - Location of the Sites Selected for Probe Compared to High Resolution Data

Figure 24 illustrates the comparison results of speed acquired from probe-based data and i2D data at Tryon Road Site 27-3 and Western Boulevard Site 28-2. The horizontal axis is i2D speed data and the vertical axis is probe-based speed data. The relative horizontal relationship indicates that the individual driver from the i2D dataset may have an independent desired speed compared to the space mean seen in the probe data.

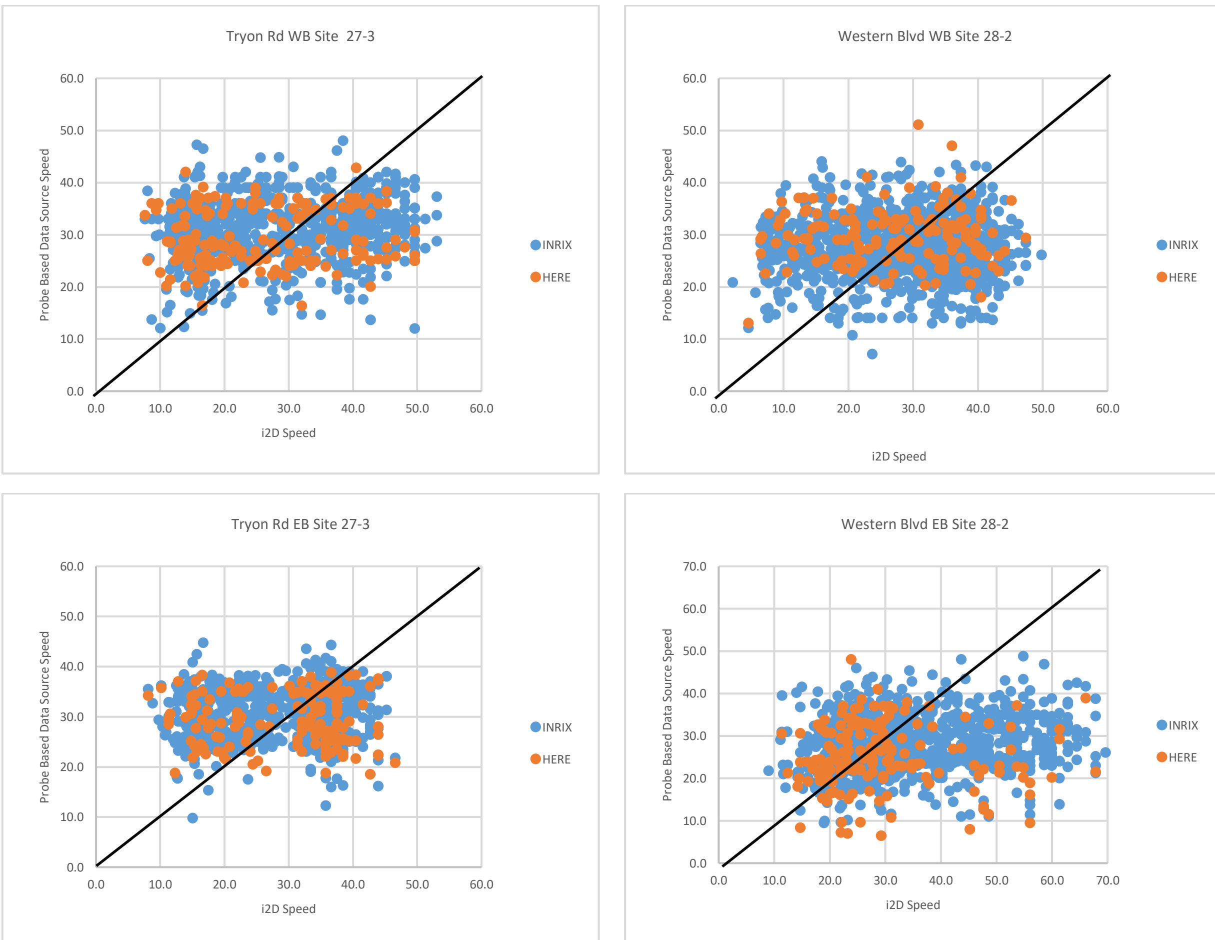

Figure 24 - Speed vs. Speed Data Comparison in Tryon Rd Site 2 and Site 3

Figure 25 compares the speed between Here.com and INRIX, which aimed to figure out the impact of different probe aggregation algorithms. Note that the x-axis is HERE.com speed data and y-axis is INRIX data speed. The comparison is done for one-minute (blue) and five-minute (black) speeds.

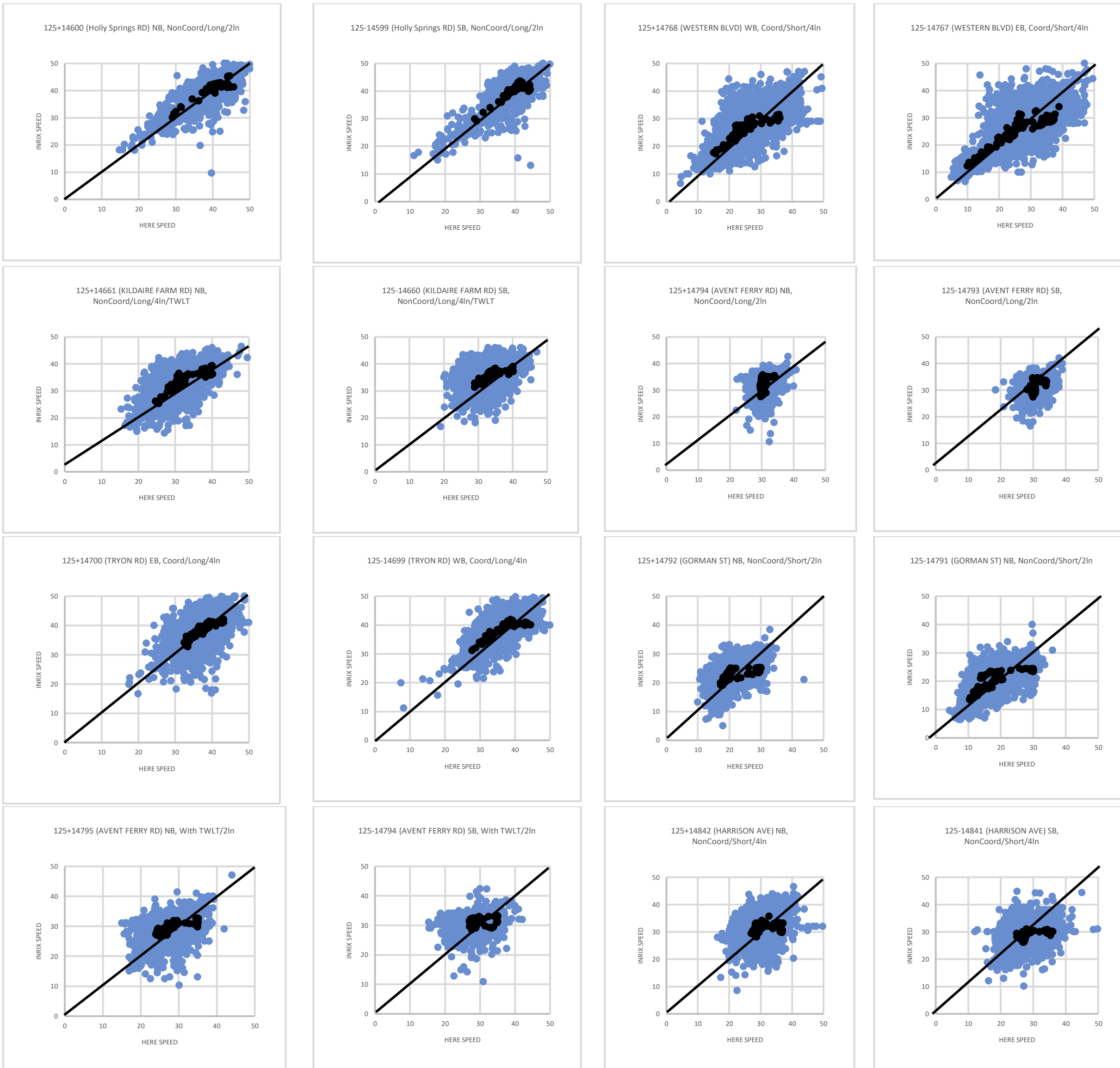

Figure 25 - Here.com and INRIX Data Comparison

From the above comparisons, it was found that the probe data has lower variabilities than i2D data, which is mainly due to the fact that the data range for i2D data is wider than probe data. This might be caused by the fact that probe data is aggregated rather than individual speeds. The probe data also contain fewer high-speed samples because the algorithm of the probe tends to underestimate vehicle speed. The aggregation of data could also contribute to this bias. In terms of data source comparison, INRIX dataset is found have a larger number of low speed samples and a smaller number of high speed samples than HERE.com dataset.

4. Lessons Learned from NCDOT Signal Prioritization Tool

4.1 Operation Platform and General Template Changes

In the previous version of NCDOT's Retiming Prioritization Signal Performance Measure (SPM) tool, the website was operated through Plotly 2 platform. The latest version of Plotly has been upgraded to 4.0. The updated Plotly platform provides users with enhanced reliability and new operational features. Plotly version 4.0 platform reduces the complexity of SPM tool in terms of future system upgrade, and offers increased potential of in-depth website development and multimedia demonstration of traffic performance data.

In addition to the upgrade of Plotly platform, interface of the new SPM tool is also changed, as illustrated in Figure 26. The color of menu bar of the website is changed to "Wolfpack Red" to keep consistency with NC State Brand Color. As shown in Figure 26 (bottom), the selected icon (i.e., "Home" icon) in the menu bar is highlighted by bold font. In addition, in the homepage, the logo of Highway Division of North Carolina Department of Transportation has been updated to its latest version. The ITRE DataLab logo is also updated.

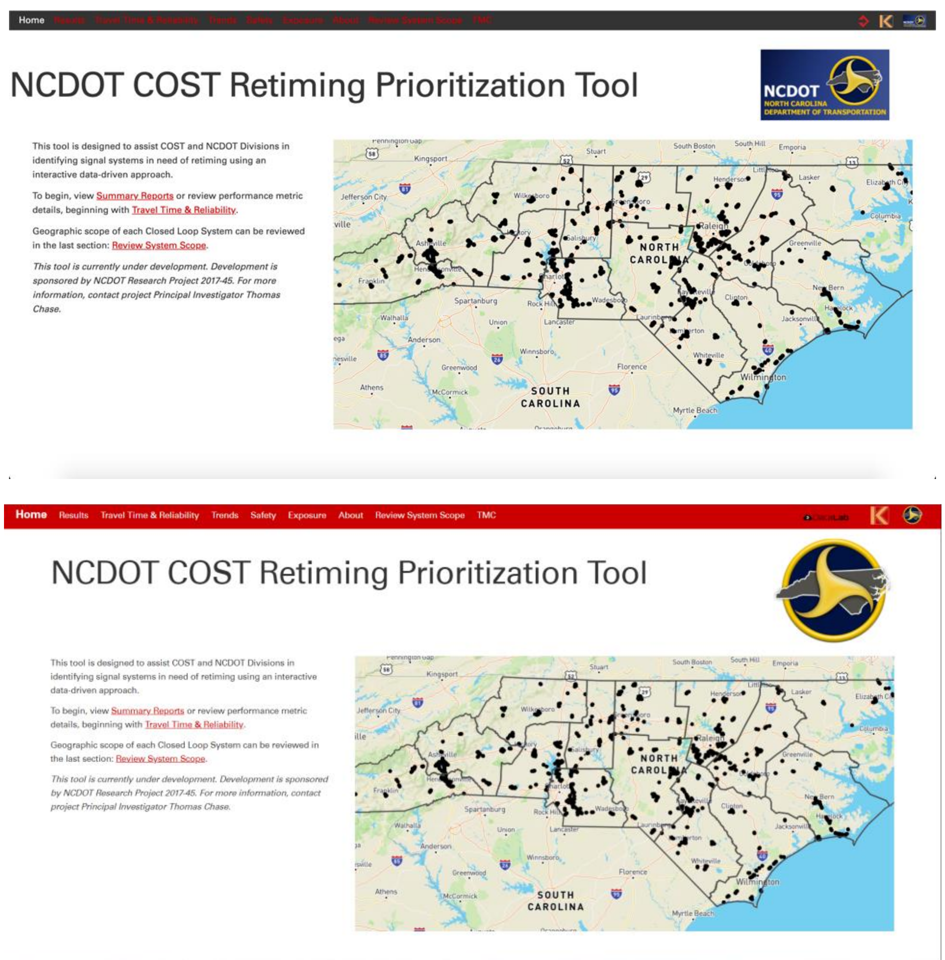

Figure 26 - SPM Tool Template Comparison （Top: SPM Tool 2, Bottom: SPM Tool 3）

4.2 Trends Page

There are two major updates in SPM trends page: radar plots and system indicator map. The radar plots of monthly traffic performance data aim to demonstrate the changes of travel time reliability within an analysis period such as within the past 12 months. Four radar plots are added to the website; each plot presented the travel time reliability in different time of the day. The travel time reliability data are categorized by year. The datapoints in the same year are connected by the same color line. Three colors lines are presented to display the travel time reliabilities of the past three years. In this report, red, green and blue lines represent travel time reliability data of 2016, 2017 and 2018, respectively. A radar plot contains 12 spokes, where each spoke represents for a month of the year. Users could easily access travel time reliability of each month and compare the changes of reliability by month. Figure 27 below illustrates an example of the AM and Mid-day Normalized Travel Time radar plot.

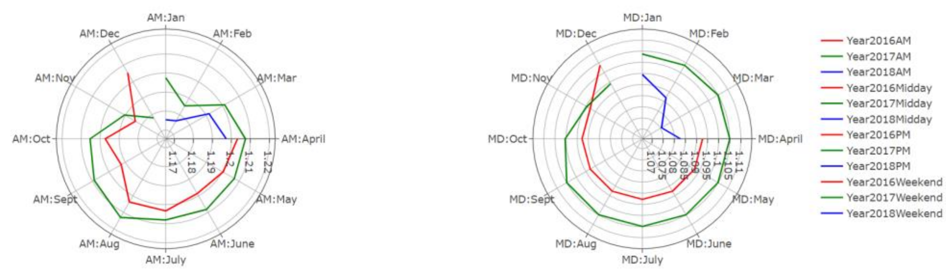

Figure 27 - AM and Mid-day NTT Radar Plots Example

Figure 28 shows the system indicator map, which is an aided tool designed for users to visualize the location of the selected system and check if the system is selected correctly. This aided tool has a built-in algorithm which could calculate the latitude and longitude coordinates of the selected system and allows for zoom in and out of the map. In addition, it allows user to analyze the adjacent facilities that potentially contribute to the changes of travel time reliability.

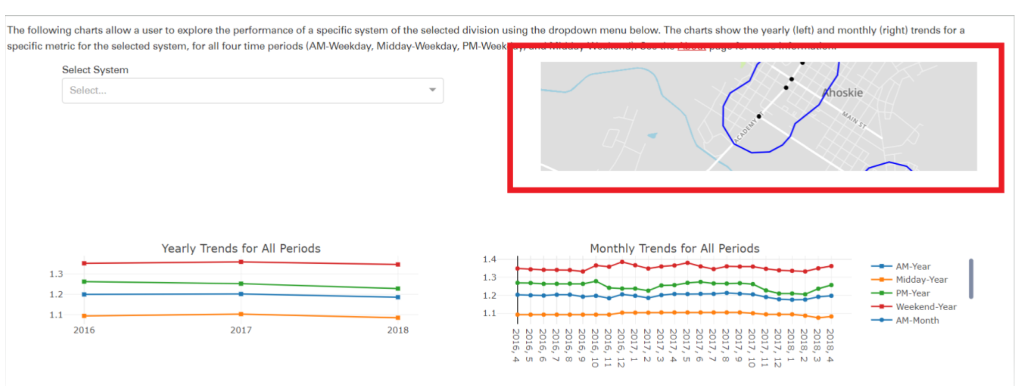

Figure 28 - Trend Layout System Indicator Map (Shown in Red Box)

4.3 TMC Page

Figure 29 demonstrates the new interface of TMC, which has been embedded in the Signal Prioritization Tool. This interface displays the changes of reliability at the TMC level. The interface has four dropdowns including: Division, System, Time of Day, and TMC. A key update to system dropdown is it includes the option of selecting different division; for each selected system dropdown, its corresponding TMC dropdown is also updated.

Below each dropdown, a TMC travel time reliability trend plot is generated and this plot could automatically update the travel time reliability data according to the TMC selected by user. The plot is NTT versus Reliability Ratio, which is the same as the one in trends layout. While the trends layout focuses on system level reliability, the TMC reliability trend plot allows user to access to TMC level reliability. Note that if an user does not select a single TMC from the previous dropdown, the plot will output the reliabilities of all TMCs documented in the selected system.

In addition, a travel time analysis plot is added as a complementary tool for users to analyze the travel time changes. Based on a metric dropdown that allows users to select time of day, users could find the annual changes of NTT, IQR or LOTTR from 2016 to 2018 in certain time of day period. The TMC dropdown options also enable users to plot the changes of travel time of either a single TMC or an aggregation of multiple TMCs.

At last, a satellite map is integrated in the TMC interface, as shown in Figure 29. The map aims to indicate the start (i.e., the green dot) and end (i.e., the red dot) points of a selected TMC, which enables users to recognize the location of the TMC. If a user did not select any TMC from dropdown, the map will display the location of the default TMC that documented in the system database.

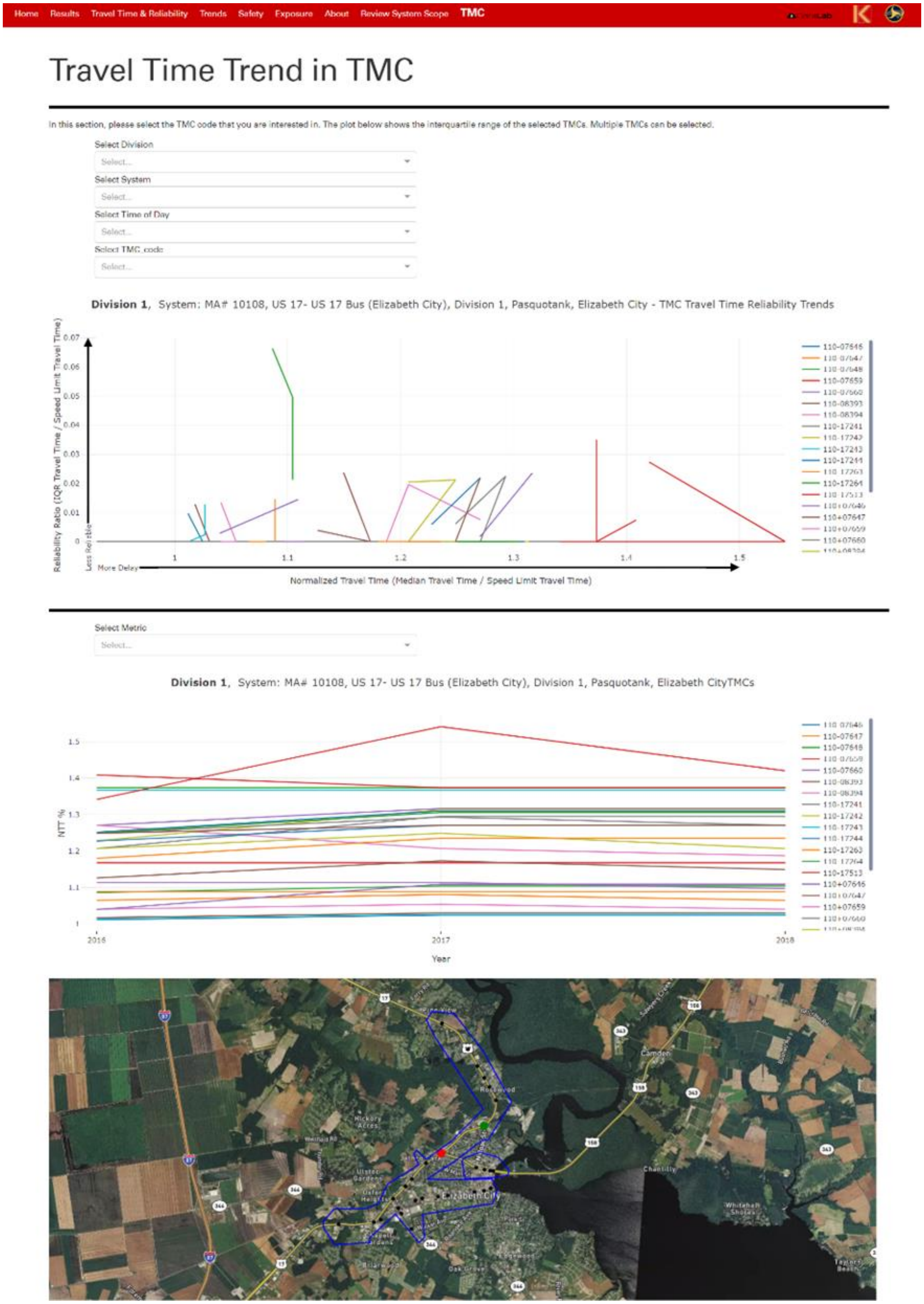

Figure 29 - TMC Layout Screen Shot

5. Conclusions, Recommendations and Future Work

From the studies listed above, we observed a data "shift" problem occurring in the HERE dataset. The distribution of the speed suddenly shifts higher or lower in a single month which is maintained for the remainder of the dataset. In seasonal impact analysis, HERE shows a significant shift pattern statewide after September 2016. In this case, the shift data may not reveal the demand or reliability change properly. The data vendor discussed with NCDOT and the research team that a change to the aggregation methodology changed at this time period and they do not expect future shifts to occur. Therefore, reliability comparison across years should remain valid aside from this time period.

The data sources were found to have different sensitivities to different dynamics of traffic. In general, INRIX and Here.com data are more sensitive compared to other probe data. Due to the Here.com data shift problem, Here.com may not provide valid data to analyze the seasonal traffic changes. But overall, the data is acceptable and appropriate. In some cases, NPMRDS should also be used in data analyzing to make sure the available data is in sufficient amount.

The research shows that the probe data is capable for calibrating the recurring and non-recurring sources of congestions in predictive tools, such as ARTVAL, Transmodeler, and Synchro. But the analyst should be careful about the reliability impacting factors existed in the interested arterial. For example, when we calibrating the weather impacted arterial, we could calibrate the models by using probe data but as found in this study, weather may worsen the arterial reliability as much as 6.3%. Utilizing all data including weather impacts for calibration of modeling tools which do not account for weather will result in erroneous performance.

The analyses presented in this report may be repeated using a number of sources and platforms available to NCDOT including NCDOT's SPM tool and Retiming tool, RITIS Probe Data Analytics, ClearGuide, and FHWA's National Performance Management Data Research Data Set. Utilization of the ARTVAL tool will enable planning-level HCM arterial reliability analysis of corridors with a limited data requirement. The utilization of the analyses and tools developed in this project will allow NCDOT to include travel time reliability in planning, managing and improving arterials in the state and measure the additional benefits to the public from these programs.

Further research into arterial reliability would benefit greatly from the utilization of additional traffic signal data which are planned to be available through NCDOT's Advanced Traffic Management System or Automated Traffic Signal Performance Measures platform. This analysis would provide additional insight into the reliability impacts of signal timing settings and time of day plan transitions.

6. References

1. U.S. Census Bureau. *2019 U.S. Population Estimates Continue to Show the Nation's Growth Is Slowing*. Release No. CB19-198, U.S. Department of Commerce, Washington, D.C., December 2019. Available: https://www.census.gov/newsroom/press-releases/2019/popest-nation.html (Accessed: July 10, 2020)
2. FHWA. *Travel Time Reliability: Making It There On Time, All The Time*. Report No. FHWA-HOP-06-070, U.S. Department of Transportation, Washington, D.C., 2006.
3. Lyman, K., Bertini, R.L. Using Travel Time Reliability Measures to Improve Regional Transportation Planning and Operations. *Transportation Research Record*, Vol.2406(1), 2008, pp.1-10.
4. Taylor, M.A.P. Travel Through Time: the Story of Research on Travel Time Reliability. *Transportmetrica B: Transport Dynamics*, Vol.1(3), 2013, pp.174-194.
5. Culotta, K., Fang, V., Habtemichael, F., Pape, D. *Does Travel Time Reliability Matter*? Report No. FHWA-HOP-19-062, U.S. Department of Transportation, Washington, D.C., 2019.
6. van Lint, J.W.C., van Zuylen, H.J. Monitoring and Predicting Freeway Travel Time Reliability: Using Width and Skew of Day-to-Day Travel Time Distribution. *Transportation Research Record*, Vol.1917(1), 2005, pp.54-62.
7. List, G.F., Williams, B. Advances in Travel Time Reliability Monitoring and Assessment. *Journal of Intelligent Transportation Systems*, Vol.21(6), 2017, pp.435-438.
8. Day, C.M., Remias, S.M., Li, H., et al. Performance Ranking of Arterial Corridors Using Travel Time and Travel Time Reliability Metrics. *Transportation Research Record*, No.2487, 2015, pp.44-54.
9. Chung, W., Abdel-Aty, M., Park, H.C., et al. Development of Decision Support System for Integrated Active Traffic Management Systems Considering Travel Time Reliability. *Transportation Research Record*, Vol.2674(2), 2020, pp.167-180.
10. Anderson, J.C., Sirupa, R., Kothuri, S., Unnikrishana, *A. Understanding Factors Affecting Arterial Reliability Performance Metrics*. NITC-RR-1117. Portland, OR: Transportation Research and Education Center (TREC), 2019. https://doi.org/10.15760/trec.240
11. Haghani, A., Zhang, Y., Hamedi, M. *Impact of Data Source on Travel Time Reliability Assessment*. Report No. UMD-2013-01, U.S. Department of Transportation, Washington, D.C., 2014.
12. Kwon, J. , Barkley, T. , Hranac, R. , Petty, K. , and Compin, N. Decomposition of Travel Time Reliability into Various Sources: Incidents, Weather, Work Zones, Special Events, and Base Capacity. *Transportation Research Record*, No. 2229, 2011, pp. 28–33.
13. Edwards, M.B., Fontaine, M.D. Investigation of Travel Time Reliability in Work Zones with Private-Sector Data. *Transportation Research Record*, No.2272, 2012, pp.9-18.
14. Hojati, A.T., Ferreira, L., Washington, S., et al. Modelling the Impact of Traffic Incidents on Travel Time Reliability. *Transportation Research Part C*, Vol.65, 2016, pp.49-60.
15. Li, Z., Elefteriadou, L., Kondyli, A. Quantifying Weather Impacts on Traffic Operations for Implementation into A Travel Time Reliability Model. *Transportation Letters*, Vol.8(1), 2016, pp.47-59.
16. Polus, A. A Study of Travel Time and Reliability on Arterial Routes. *Transportation*, Vol.8, 1979, pp.141-151.
17. Taylor, Michael AP and Somenahalli, Sekhar. Travel Time Reliability and the Bimodal Travel Time Distribution for an Arterial Road. *Road & Transport Research: A Journal of Australian and New Zealand Research and Practice*, Vol.19(4), 2010, pp.37-50.
18. Yang, F., Yun, M., Yang, X. Travel Time Distribution Under Interrupted Flow and Application to Travel Time Reliability. *Transportation Research Record*, No.2466, 2014, pp.114-124.
19. Pu, W. Analytic Relationships Between Travel Time Reliability Measures. *Transportation Research*

Record, No. 2254, 2011, pp. 122-130.
20. Li, Q., Ma, J., Ghamami, M., Nie, Y. Urban Travel Time Reliability Analysis with Consumer GPS Data. *Transportation Research Record*, No.2497, 2015, pp.73-83.
21. Zhang, X., Hamedi, M., Haghani, A. Arterial Travel Time Validation and Augmentation with Two Independent Data Sources. *Transportation Research Record*, No.2536, 2015, pp.79-89.
22. Zheng, F., Liu, X., van Zuylen, H., et al. Travel Time Reliability for Urban Networks: Modelling and Empirics. *Journal of Advanced Transportation*, Vol.2017, https://doi.org/10.1155/2017/9147356
23. Glick, T.B., Figliozzi, M.A. Traffic and Transit Travel Time Reliability Indexes and Confidence Intervals: Novel Methodologies for the Corridor and Segment Levels. *Transportation Research Record*, No.2649, 2017, pp.28-41.
24. Singh, V., Gore, N., Chepuri, A., Arkatkar, S., Joshi, G., Pulugurtha, S. Examining Travel Time Variability and Reliability on An Urban Arterial Road using Wi-Fi Detections – A Case Study. *Journal of the Eastern Asia Society for Transportation Studies*, Vol.13, 2019, pp.2390-2411.
25. Tufuor, E.O., Rilett, L.R. Validation of the Highway Capacity Manual Urban Street Travel Time Reliability Methodology using Empirical Data. *Transportation Research Record*, Vol.2673(4), 2019, pp.415-426.
26. Elefteriadou, L., Lu, C., Li, Z., Wang, X., Li, J. *Multimodal and Corridor Application of Travel Time Reliability*. Report No. BDK77 977-10. Florida Department of Transportation, Tallahassee, FL, 2012.
27. Elefteriadou, L., Li, Z., Jin, L. *Modeling, Implementation, and Validation of Arterial Travel Time Reliability*. Report No. BDK 77-977-20. Florida Department of Transportation, Tallahassee, FL, 2013.
28. Torrisi, V., Lgnaccolo, M., Inturri, G. Estimating Travel Time Reliability in Urban Areas through A Dynamic Simulation Model. *Transportation Research Procedia*, Vol.27, 2017, pp.857-864.
29. Tanvir, S., Chase, T., Rouphail, N. Development and analysis of eco-driving metrics for naturalistic instrumented vehicles. *Journal of Intelligent Transportation Systems*, 2019, DOI: 10.1080/15472450.2019.1615486.
30. Davis, J., Chase, T., Aghdashi, B., Cunningham, C., Head, W., Poslusny, J. and Karlson, T., 2019. *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways Final Report*, FHWA/NC/2018-19, North Carolina Department of Transportation, Raleigh, NC.