VOLUME I

Monitoring Travel Time Reliability

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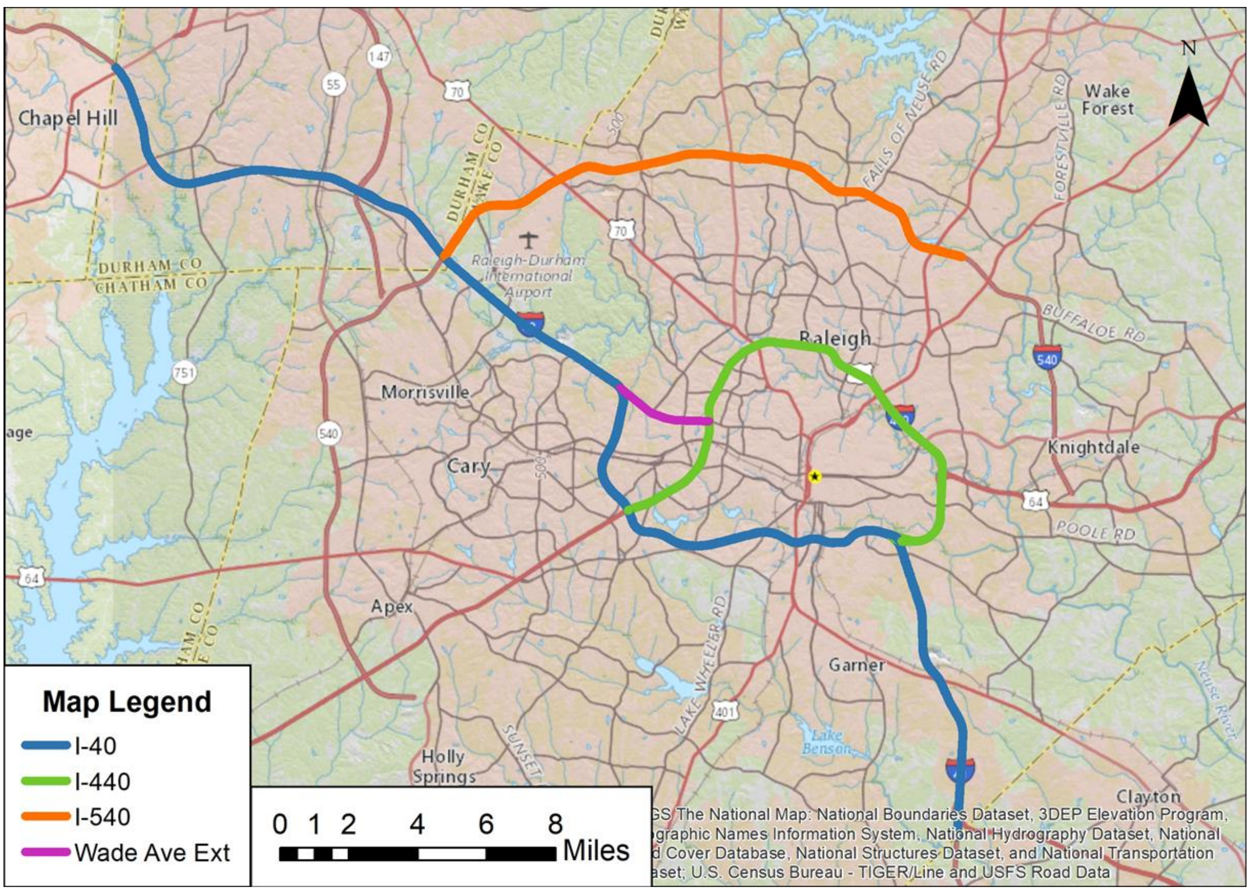
I-1. INTRODUCTION

This volume of the final report presents the application of ideas from SHARP2 L02(1) to a case study setting in North Carolina. The setting chosen, depicted in Exhibit I - 2, comprises sections of I-40, I-440, I-540, and Wade Avenue Extension in Raleigh, NC. These are freeway segments for which data were available to do the case study: travel rates, flow rates, incidents, weather, and planned events. The study year was 2010. As will be explained later, the observations were assembled at the granularity of 5-minutes for all Traffic Message Channel (TMC) segments in the network. With 365 days in the year, this means there were 105,120 5-minute observations of travel rates, flow rates, incidents, weather data, and planned events for each of 206 TMC segments. Thus, the database comprised more than 21 million observations for each of the four data categories, or roughly 84 million data points overall.

Exhibit I - 1: The Study Network for the L02 Case Study



The case study involved: 1) data fusing to identify the causes of aberrant travel times (and rates); 2) imputation to fill holes in the data sets; data categorization and analysis as suggested by L02 to analyze the performance of segments and routes; 3) travel time stitching methods to generate more refined values of TMC- and route-level travel times and rates; and 4) cumulative distribution functions (CDFs), probability density functions (PDFs), and delay measures to assess the performance of TMC segments and routes.

Project L02 presented methods by which transportation agencies could monitor and evaluate travel time reliability. Those methods also produced an improved understanding of why and how travel times vary and the factors that create that variation.

This section of the final report describes the outcomes of these efforts and the processes employed to develop the findings. Section 2 describes the processes used to assemble the data. Section 3 presents the outcomes from the analyses. Section 4 identifies the conclusions obtained and the recommendations ensuing from the effort.

I-2. METHODOLOGY

The methodology used in this analysis involved the following eight-steps. This process is an advance over the process established by SHRP2 L02 in that it provides more indepth guidance beyond SHRP2 L02's four-step – *Imputation*, *Segment travel time calculations*, *Route travel time calulations*, and *Influencing factor analysis* – process.

1) *Gather the travel rate data*. These are the rates (for example, minutes/mile) at which traffic was traversing the TMC segments during each 5-minute interval for every TMC segment during the study year. In the case of the study network, these data were gathered by INRIX as space-mean speeds, based on probes. These speeds were obtained from RITIS, which is used by NCDOT as the repository for such information. Temporal stitching algorithms were then applied to produce more defensible travel rates for each TMC and time interval. This is described in more detail later.

2) *Gather operating condition data*. Every travel rate observation is produced by an operating condition. The TMC segment is subjected to a specific demand (flow rate) for a weather condition plus other influences such as the presence (or absence) of an incident, a work zone, a planned event, lane closures, nearby events, etc. Describing the operating condition correctly is critical if the mitigating actions are to be correctly identified.

3) *Identify Normal / Abnormal Performance*. The next step is to divide the observations into those that have arisen during "normal" operating conditions as opposed to "abnormal" conditions. Normal is typically seen to be the operating condition when no adverse influences are in play from weather, incidents, work zones, special events, or other activity (e.g., a fire on a nearby property). Put another way, it is the conditions that would be "expected" for that TMC and time interval. Abnormal is everything else. Effectively, reliability assessment is about identifying the causes for the abnormal operating conditions and then identifying mitigating actions that can be taken to improve performance during those conditions and/or eliminate their occurrence.

4) *Label observations with explanations*. This is the process of adding one or more labels to each observation that indicate the operating conditions under which the travel rate arose. This includes flags for adverse weather, incidents (e.g., number of lanes closed), work zones, etc.

5) *Select / define analysis conditions*. After labeling the observations, the next step is to identify (define) the conditions for which the performance is to be assessed. In the context of the MAP 21 guidelines (2), it is the entire year and all operating conditions. Alternately, agencies may be interested more narrowly in the performance under normal PM peaks, AM peaks during adverse weather, AM or PM peaks during incidents, Friday afternoons in the summer when vacation traffic is high, etc. As the asterisk comment indicates, it is critically important that the analyst and the audience understand these conditions in the same way.

6) *Conduct the analyses*. This step involves developing the CDFs and PDFs that describe the operation of the TMC segments included in the analysis (either separately or jointly as in a subnetwork or a route). If a single operating condition is examined (e.g., snow days in the winter), then there may be only one CDF, and the question being answered is: what is the nature of the CDF. (Then the subsequent question can be posed: what can be done to improve performance.) If more than one operating condition pertains (e.g., all observations for the PM peak are considered, and sometimes weather is an issue, or incidents, or planned maintenance). Then, multiple CDFs are produced. They can be compared. Performance can be assessed. The question can then be posed: How can the performance under the adverse conditions be improved so that the difference from normal conditions is reduced?

7) *Draw conclusions / prepare recommendations*. This step, which is outside the bounds of the effort presented here, but is the focus of the material presented in Volume II, asks the question, what can be done to improve performance. What the analysis presented here does is to defensibly describe the changes in performance that arise between and among the operating conditions.

8) *Gather additional operating condition data*. It is quite possible that the analysis leads to conclusions that the observed behavior is not being described either adequately or correctly. In the first case, not enough operating condition information has been collected to correctly label the observations (e.g., there was an incident and it went unrecorded; or there was an incident on a nearby facility (e.g., a cross-street) and it was not identified. In the second case, TMC segments upstream of the reported location of the incident were affected by the incident (e.g., their travel rates were abnormally high), but no label(s) were added to the observation to indicate that this was the case. Hence, the aberrant behavior was being observed without explanation, which does not help when identifying mitigating actions.

I-3. DATA PREPARATION

This section describes how the datasets were assembled and prepared for analysis. The data comprised observations of 1) travel rates, 2) weather, 3) incidents, 4) flow rates, and 5) planned events for each of four facilities (I-40, I-440, I-540, and Wade Avenue Extension), in both directions, for every 5-minute interval and TMC segment during 2010.

I-3.1. Travel Rates

Because NCDOT is a member of the I-95 Corridor Coalition, the study team could access speed and travel time data sourced by INRIX for the 2010 via the Vehicle Probe Project (VPP) within the Regional Integrated Transportation Information System (RITIS) (3). These data are spatially organized by Traffic Message Channel (TMC) segments, a directional spatial segmentation protocol created by navigation companies Navteq and TomTom. TMC segments are either internal or external to interchanges. Segmentation changes at entry and exit ramps. While the project focused on freeway facilities, the database includes information about arterials, ramps, and other surface streets. The raw data can be aggregated into average values for one, five, and 15-minute intervals. This analysis used 5-minute aggregation intervals to dampen the effects of subtle variations within the traffic stream and yet capture variations that occurred across the peak traffic load conditions.

Missing temporal intervals were added to the dataset and linear interpolation was utilized to fill gaps of two or fewer temporal observations, 10 minutes in total, for both types of data errors. Temporal gaps less than 10 minutes were interpolated between adjacent temporal observations for the same TMC segment to maximize the number of time/space observations included in the generated distributions. Gaps greater than 10 minutes were not addressed to avoid introducing additional error into the dataset.

The length of each TMC segment was extracted from a separate CSV file containing information about the TMCs. Location data was provided in start/end geographic coordinates and the length of each TMC segment was provided in miles. Due to frequent changes to TMC segmentation to account for new interchanges, ramps, etc., the location data from the characteristics file were used to develop a shapefile of TMC segments used to spatially assign other datasets to the TMC-based segmentation.

Stitching algorithms were employed based on earlier research presented by Chase et al. to account for spatial and temporal boundary conditions (4). TMC segments served as virtual boundaries to facilitate georeferenced data collection of vehicle speed data. Trajectories were generated for ten hypothetical vehicles that enter the TMC segment-based facility every 30 seconds during each 5-minute interval. Based on the aggregated speed value reported by RITIS, an algorithm determined if the vehicle would reach the end of the TMC segment by the end of the five-minute observational period and tabulate the travel time to traverse the segment. If the vehicle completely traversed the spatial segment within the observational period, the travel rate was tabulated using the travel time and the length of the TMC segment. However, if the vehicle's trajectory did not reach the end of the TMC segment, the trajectory speed was updated to the reported average speed for the next temporal interval and so forth until the vehicle crossed the end of the TMC segment. The travel time for such vehicles to traverse the TMC segment was then divided by the length of the TMC segment to determine the travel rate. All ten travel rates for the synthetic vehicle trajectories were then averaged.

I-3.2. Flow Rates

During 2010, the study year for the case study, 60 side-fire radar sensors were actively deployed across the Research Triangle interstates, I-40, I-440, and I-540. Here.com administered data collection from these units and compiled datasets of speed, volume, and occupancy for each lane. Data from these sensors were obtained from ITRE's archive of side-fire radar data. While flow rate data are not required for a reliability monitoring system, the data further enhances the analysis of the travel time data.

Lane-by-lane traffic flow data collected from the HERE side-fire radar sensors were aggregated into 5-minute totals by direction. These flow rate data, which are measured at a point location, were assigned to TMC segments based on spatial proximity based on the geographic coordinates provided along with the flow rate data and visual assignment to the TMC segments along the facility. For limited-access freeway facilities, flow continuity was assumed between interchanges, allowing for the application of point data to sequences of TMC segments. Generally, at least one sensor was located within each interchange and between all interchanges. If a single sensor was located within a TMC segment, the volumes measured by that sensor were assigned to that segment. If more than one sensor was located within a TMC segment, all sensors along the segment were averaged. If a sensor was not located along a TMC segment, the nearest sensor up and downstream of the segment were averaged and assigned to the TMC segment. Five-minute volumes were multiplied by twelve to represent effective hourly flow rates for comparison with other flow rate-based capacity metrics. A heavy vehicle factor based on 2% heavy vehicles was applied to the flow rate data to covert the data into passenger cars per hour per lane (pc/hr/ln), consistent with the guidance provided by the Highway Capacity Manual (5).

I-3.3. Incidents

Incident data for Durham, Johnson, and Wake counties were obtained from NCDOT's Traveler Information Management System (TIMS) database for 2010 (5). TIMS provides real-time and updated information to users about incidents and congestion along the freeways and major arterial routes across the state. Incidents reported in TIMS include unplanned events such as vehicle collisions and breakdowns as well as planned work zones and special event detours. Each unique incident is assigned an ID number and the record includes the start and end times, milepost locations, geography coordinates, the number of lanes blocked, type of incident, and a general description of the event. This information comes from staffers working in the Statewide Operations Center (STOC), a traffic management center with access to public safety communication channels and video feeds from cameras located throughout the network. Incident data was utilized in contrast to crash report data from the Division of Motor Vehicles due to the focus on traveler impact. TIMS only includes incident events deemed to impact the traffic stream, while crash reports are generated for every event, regardless of severity or impact to the traffic stream.

Both planned and unplanned incidents are reported in TIMS to maintain a central source for information about events that adversely impact traffic (6). For the purposes of the monitoring system, vehicle collisions and breakdowns were classified as unplanned and road construction events were classified as planned. The analyst can further refine the incident definition to for example, isolate incidents with lane closures or select only collisions.

Incident data in TIMS includes both latitude/longitude and statewide milepost spatial extents of the incident location. However, only one set of geographic coordinates were reported for each incident. Vehicle-based incidents were spatially assigned to TMC segments based on the coordinate data. The spatial extent of these incident types was most commonly one segment. However, planned work zones could stretch over many miles and TMC segments. Therefore, the starting and ending mileposts were utilized to spatially locate these incidents to TMC segments.

Mileage-based exit numbering schemes number interchanges based on the nearest state milepost. In general, state mileposts start at the western or southern border increasing until the next state border or facility terminus. Auxiliary loop and spur routes within the interstate system such as I-440 and I-540 start mile posting from the southern or western terminus. As a tool to inform the public, TIMS uses the state mileposts to locate incidents. However, road characteristic data provided by NCDOT utilized a county-based milepost referencing system. Therefore, spatial data for the location of each milepost sign, provided in a shapefile from NCDOT, were utilized to assign TMC segments to incidents with a spatial extent beyond one TMC segment. Several mileposts were missing and visual estimation was used to locate incidents that terminated at a milepost not included in the dataset. Incident spatial assignment was performed visually by displaying the shapefiles and feature classes in ArcGIS.

I-3.4. Weather

Two types of weather data were obtained: observational data from local weather stations adjacent to the freeway facilities and adverse weather warnings issued by the National Weather Service, specifically, the NWS forecasting office in Raleigh (7). Shapefiles containing spatial, temporal, and categorical data for warnings issued by the NWS were obtained from the Iowa Environmental Mesonet center at Iowa State University (8). Data from five weather stations across the study area were obtained from the State of North Carolina Climate Office, a governmental agency that provides climate data to other state agencies, educational, and commercial users (9). The weather stations were in Clayton, NC, at Lake Wheeler south of

Raleigh, at the Reedy Creek Research Station in Raleigh, at Raleigh-Durham International Airport (KRDU) and at the Horace Williams Airport in Chapel Hill NC.

The sixth edition of the Highway Capacity Manual was used to set precipitation thresholds (5). Light rain is defined as an hourly precipitation rate less than one-tenth of an inch per hour. Moderate or medium intensity rain is characterized by precipitation rates between 0.1 and 0.25 inches per hour. Precipitation rates greater than a quarter of an inch per hour are considered heavy rain. If the measured air temperature was below freezing, 32° F (0° C) while precipitation is recorded, the precipitation is noted as freezing. The type of freezing precipitation cannot be determined directly from the precipitation and air temperature data. Snow events in the region are so infrequent that reliability during accumulating snowfall is not expected by users and measures to improve reliability may be economically infeasible for the seasonal average snowfall amounts observed in the region.

NWS warning data complimented the observational data by capturing severe weather warnings communicated to the public, specifically over emergency radio broadcasts. Warnings are generally disseminated via local Emergency Alert System (EAS), a Federal Communication Commission (FCC) program that requires almost all audiovisual broadcasting outlets, including radio and television, to display warning information. These warnings inform motorists already on the road that action may be required to maintain safety. Warnings observed elsewhere may encourage users to delay or reschedule a trip rather than start a trip during the warning period (10). For conducting the case study, all warnings were weighted equally, whereas user response to warnings vary by warning type.

I-3.5. Planned Events

Special-demand generating events account for time periods when a facility experiences significantly above normal traffic demand resulting from an event such as an athletic event, concert, fair, etc. These types of events occur infrequently enough such that the adjacent roadway network is not designed to accommodate the extra demand. Within the Research Triangle, PNC Arena and Carter-Findley Stadium offer examples of what does and does not constitute special demand-generating events. PNC Arena is a multipurpose arena with an approximately 19,000-person capacity that serves as the home venue for North Carolina State University's men's basketball team and a professional hockey franchise in addition to numerous concerts and other one-off events. Located adjacent to I-40, I-440, and Wade Avenue, arena traffic is generally absorbed by those freeway facilities and traffic impacts are limited to the adjacent arterials connecting the arena to the freeways.

Carter-Findley Stadium hosts home games for NCSU's football program and has a capacity of approximately 55,000. Occasionally, once every few years, outdoor concerts will be held at the stadium drawing approximately 40,000 people. Most college football games at the stadium are hosted on Saturday afternoons, when background traffic demand is low compared to weekday traffic flows. Like PNC Arena traffic, saturday football traffic is generally absorbed by the adjacent freeways with local facilities experiencing the most significant traffic impact. However, most concerts and the occasional football game occur on a weeknight and attendees are traveling to the stadium during the evening peak hour when background demand is at its highest. Traffic congestion from the additional traffic can materially affect conditions on the adjacent freeways and have transient effects on the regional network. The concerts and weekday football games would be classified as special-demand generating events, whereas the arena events and Saturday football games would not.

I-4. FINDINGS

Combinations of external events and study periods were selected to show how the L02 techniques could be used to do reliability assessments. Normal observations were identified by the lack of an external event flag. All other observations deemed abnormal. Due to the number of valid samples in the dataset, normal/abnormal categories were applied to the AM, PM, and weekend peak hours while all temporal observations were included in the subgroupings of incident-only, weather-only, and observations with both active weather and incident events. The flow rate flag nominally is based on the travel rates. The flow rate data per se were not considered. A separate flow rate dataset is generated and paired with the geometric characteristics of each TMC segment, including the number of lanes and the free flow speed. Oversaturated demand considitions were identified by comparing the estimated flow rates to the HCM pc/hr/ln capacity thresholds.

I-4.1. Facility-Wide Assessment

Facility-wide assessments were prepared for all four freeway facilities in both directions (8 total). The analysis of I-40 eastbound is described here briefly as an example. More complete results for this example and the findings for the other freeways and directions can be found in Appendix I-B.

Temporally stitched travel rates were created for all TMC segments and time intervals. Travel rates were used instead of times so that comparisons could be conducted between TMCs of different lengths. Missing time/space travel rate observations were imputed for instances where the temporal gap for a given TMC was no more than 10 minutes (two missing observations).

Operating condition flags were added for all abnormal conditions, such as weather, and incidents (including planned events) as described earlier. The observations were then categorized as belonging to one of these operating conditions, including "normal". If one or more flags were set, the observations were first classified as abnormal, and then further categorized based on the combinations of flags that were set (e.g., weather and an incident).

Analyses were conducted for each facility, both overall and for three spatially distributed TMCs. The TMC segments selected for I-40 eastbound were 125-04870, 125-04857, and

125N04836. 125-04870 is a three-lane segment adjacent to the NC 751 interchange in western Durham County at exit 274. 125-04857 has three through lanes and is located near the Cary Towne Blvd / Farm Gate Rd. at exit 2910. 125N04836, a two-lane segment, is located at the US 70 Business interchange in southwestern Wake County. Exhibit I-10 contains summary data for each of the highlighted TMC segments. More details about these TMCs can be found in Appendix I-B.

CDFs and other summary statistics were generated for normal and abnormal observations as defined by the flags that were set. The buffer time index, ratio of the difference of the 95th percentile and 50th percentile travel rate to the 50th percentile travel rate, were also generated to facilitate comparison with other reliability studies. The buffer time index was also tabulated for each scenario. All TMCs for each facility direction were ranked by buffer time index for the AM peak period, PM peak period, weekends, and 24-hour analysis periods.

Distributions of the space-mean speeds (from the travel rates) were also prepared. These distributions were then tabulated and plotted to indicate the frequency with which speeds were above 60 mph and in ranges below 60 mph for each temporal analysis period (AM, PM, and weekend).

Exhibit I - 2 shows the AM peak and PM peak speed distributions for 125-04870, 125-04857, 125N04836, and all I-40 EB TMCs. TMC 125-04857 shows significant variations, especially during the PM peak period. Only about 30% of reported travel speeds are greater than 60 mph during that temporal analysis period. 125-04870 has the highest number of reported travel speeds greater than 60 mph for all temporal analysis periods, likely due to the lane addition just upstream of this TMC segment. In general, more variation is observed during the PM peak period than the AM peak period.

Exhibit I - 2: AM and PM peak travel speed distributions for the entire facility and three selected TMCs

	125-04870	125-04857	125N04836	Facility
AM Peak Period				
60+	96.73%	78.88%	98.75%	95.37%
55 - 60	1.20%	15.68%	1.03%	2.85%
45 - 55	0.43%	3.51%	0.17%	0.89%
40 - 45	0.19%	0.46%	0.02%	0.19%
30 – 40	0.39%	0.62%	0.01%	0.26%
15 - 30	0.63%	0.57%	0.01%	0.28%
0 - 15	0.43%	0.28%	0.02%	0.15%
PM Peak Period				
60+	96.17%	29.75%	72.77%	77.85%
55 - 60	2.29%	25.57%	4.63%	6.59%
45 - 55	0.63%	32.68%	4.81%	4.62%
40 - 45	0.11%	7.26%	2.78%	1.63%
30 – 40	0.19%	3.07%	6.76%	3.33%
15 - 30	0.32%	1.40%	7.06%	4.90%
0 - 15	0.29%	0.27%	1.19%	1.08%

Exhibit I - 3 and Exhibit I - 4 respectively show CDFs of the 24-hour data for normal and abnormal conditions for the three selected TMCs over the 24-hour analysis period.

Exhibit I - 3: CDF plots of 24-hour normal travel rates for three I-40 EB TMC segments

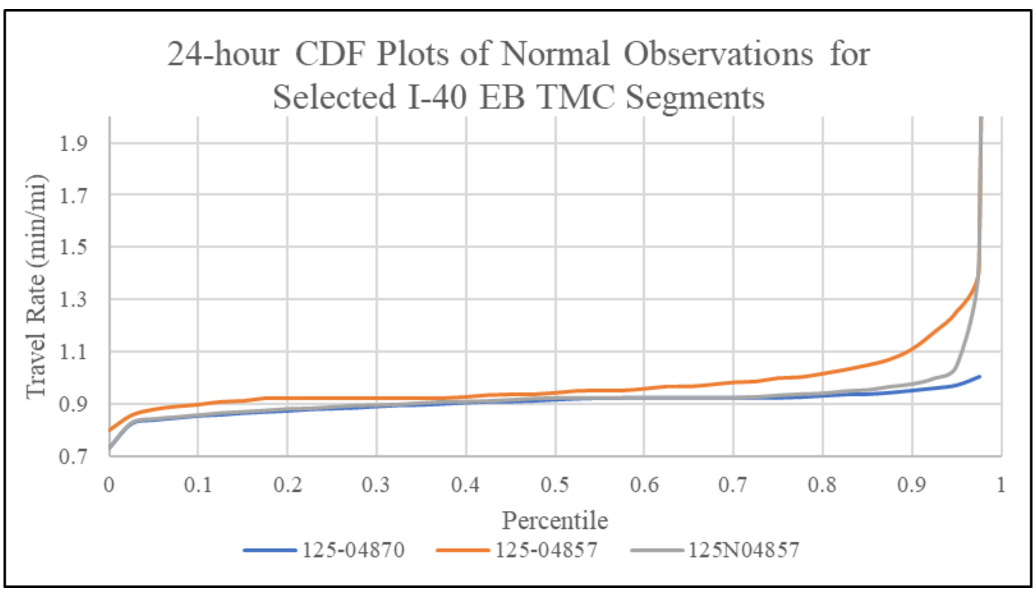
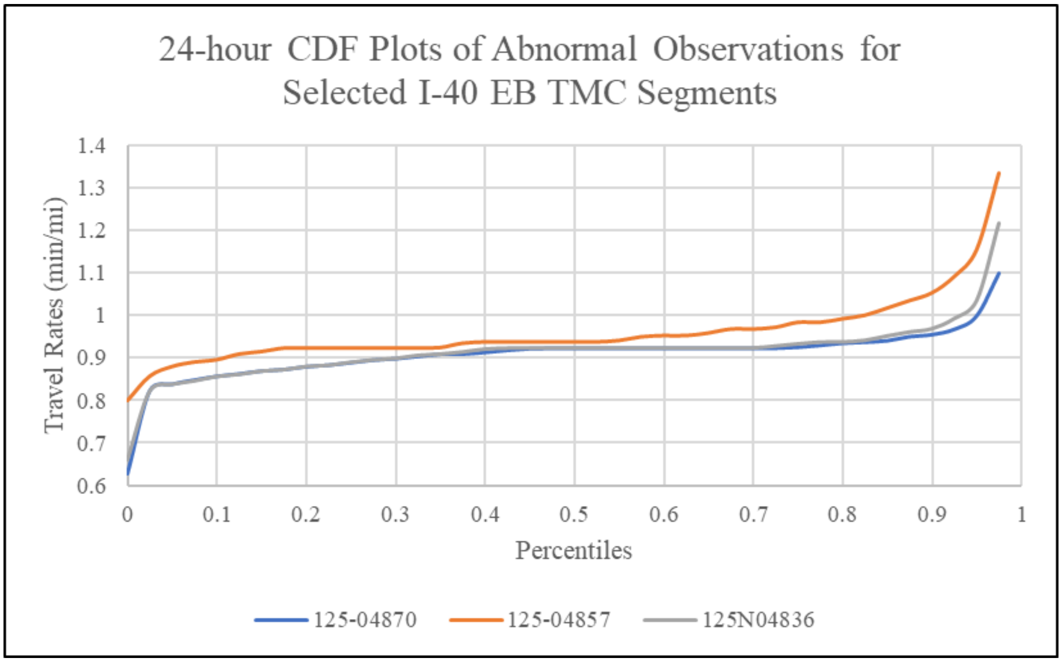
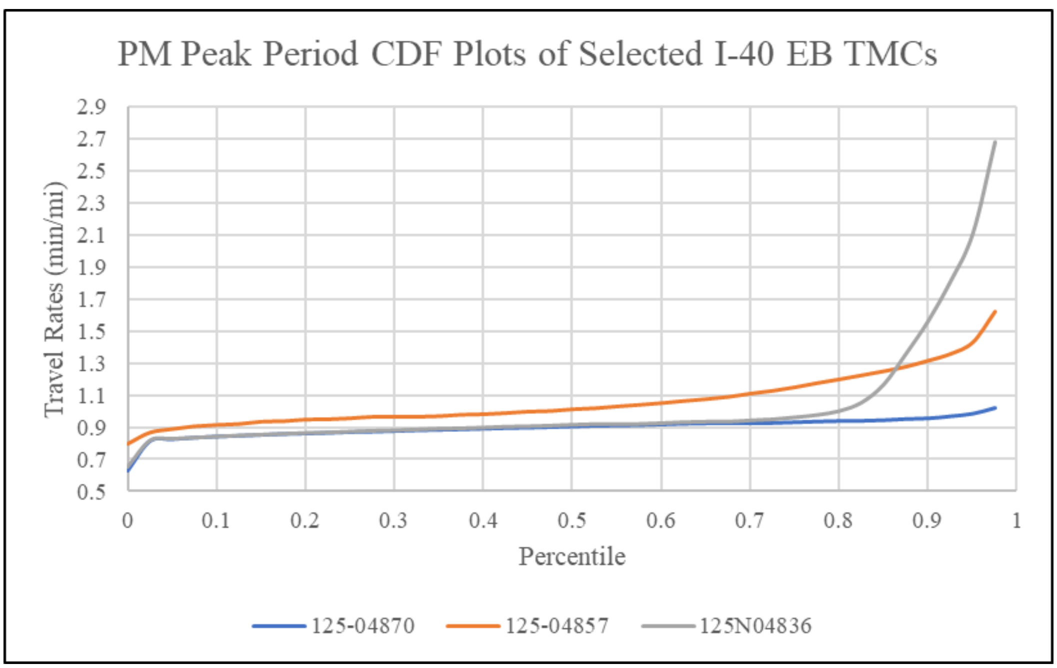


Exhibit I - 4: CDF plots of 24-hour abnormal observations for three I-40 EB TMC segments



The PM peak was the worst performing temporal analysis period for each of the TMCs as indicated by the speed distributions. Exhibit I - 5 shows CDF plots for the normal observations during the PM peak period.

Exhibit I - 5: CDF plots of PM peak normal travel rates for three I-40 EB TMC segments.



Distributions were also generated for various combinations of external events over all time intervals. External events were broken down into incidents only, weather only, and incident plus weather. Exhibit I - 6 displays CDF plots of abnormal condition travel rate distributions for all time intervals.

I-4.2. Route-Based Assessment

Route-based assessments provide additional insights into facility performance. This is because the routes are serial combinations of TMCs and poor performance on one TMC can be offset by good performance on another. Analysis of routes typically traversed by users provides metrics in a more relevant spatial context for the traveling public. Route travel rate analyses were distinguished from individual TMCs by the spatial and temporal stitching algorithm that aggregates TMC travel rates along a route composed of multiple and consecutive TMC segments. In this section an eastbound route from I-40 at Davis Drive (RTP) to the interchange of I-440 with US 64 (business) is examined. The route involves TMCs along I-440 EB, Wade Ave EB, and I-440 EB. Valid vehicle probe data was only available for about half of the temporal intervals during 2010, therefore, the sample of constructed route travel rates is significantly smaller than other routes and facility analyses. Based on the results of an analysis shown in Appendix B, the normal/abnormal threshold was set at two-TMC flags for each event type. For these criteria, speed distributions were generated for both normal and abnormal conditions during each temporal analysis period

Exhibit I - 6: CDF plots of external event operating conditions during all time intervals for selected I-40 EB TMC segments.

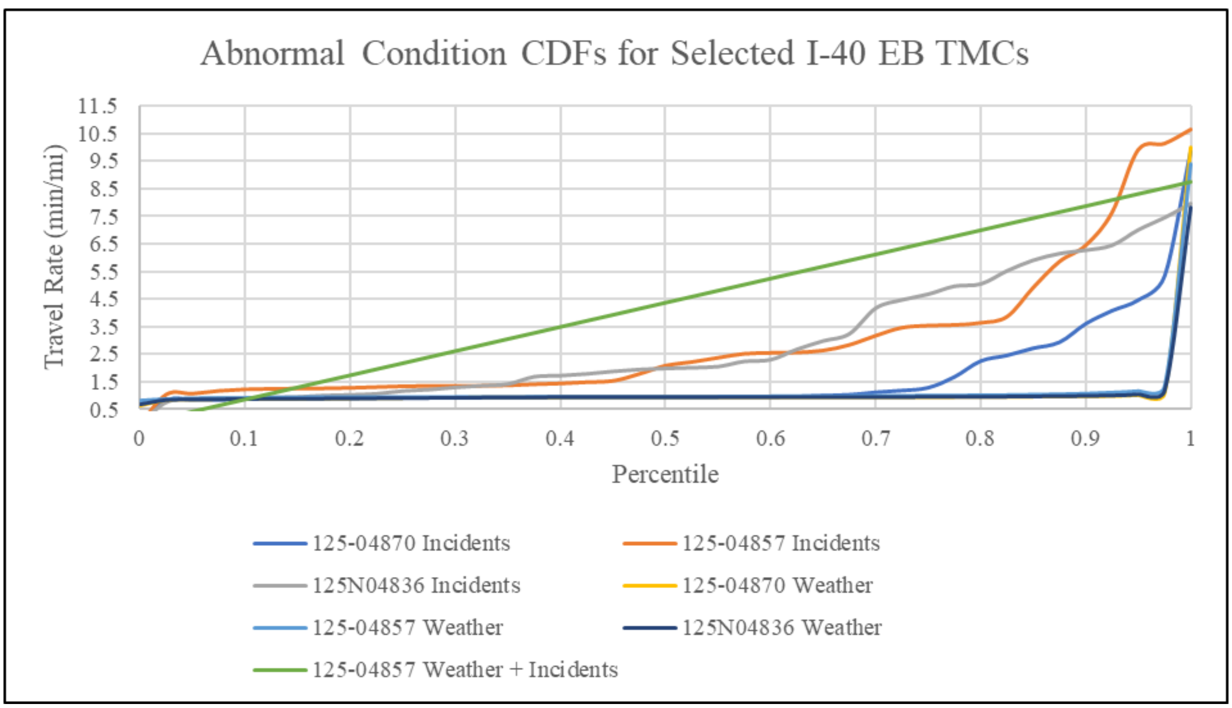


Exhibit I - 7 displays CDFs for the travel rates involving both normal and abnormal observations. The normal and abnormal distributions generally tracked each other, suggesting that average rates calculated over an entire route even out some of the impact generated by external events. The AM peak period indicates that speeds started to fall below 60 mph at the 60th percentile compared to the 85th percentile for the 24-hour distributions. Even though speeds decrease during the PM peak period as indicated by the speed distribution, the normal observation PM distribution did not sharply increase at the upper end of the distribution.

Exhibit I - 7: CDF plots of normal and abnormal conditions for the AM and PM peak periods

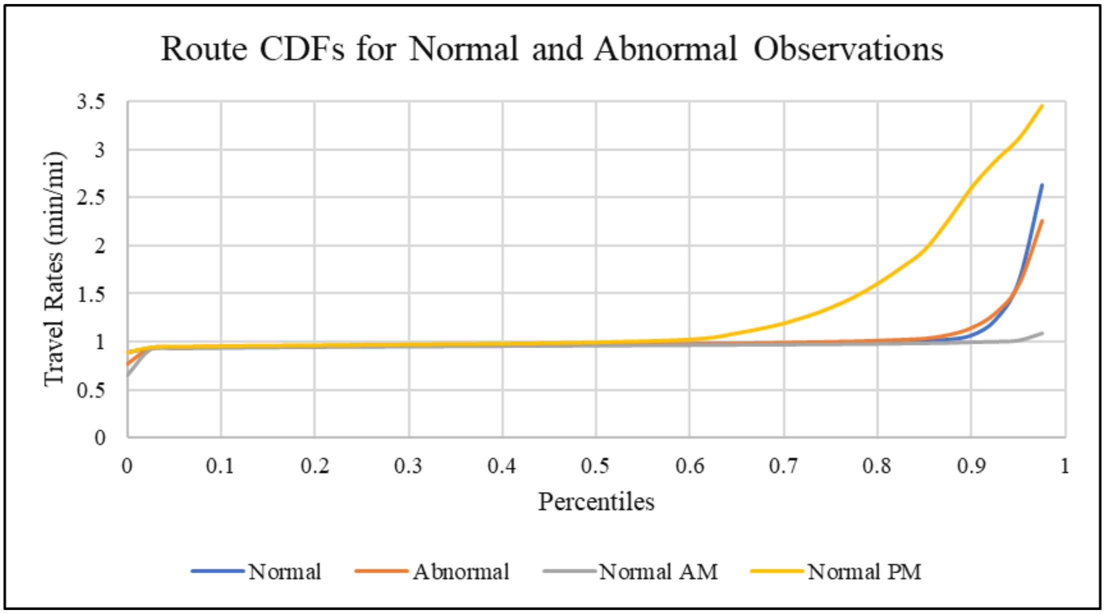


Exhibit I - 8 displays the generated speed distributions observed along the route. For all temporal observations, there was an approximately 6% decrease in observed speeds greater than 60 mph from normal conditions to abnormal conditions.

Exhibit I - 8: Route speed distributions for both normal and abnormal operating conditions for each temporal analysis period

	24-Hour	AM Peak	PM Peak	Off-Peak	Weekend
Normal					
60+	82.58%	73.36%	63.64%	89.50%	85.38%
55-60	11.15%	11.81%	14.34%	9.34%	11.95%
45-55	3.15%	7.42%	10.19%	0.77%	1.52%
40-55	0.87%	2.20%	2.76%	0.15%	0.50%
30-40	1.13%	2.66%	4.01%	0.16%	0.53%
15-30	1.08%	2.41%	4.89%	0.08%	0.13%
0-15	0.04%	0.12%	0.16%	0.00%	0.00%
Abnormal					
60+	76.32%	54.50%	60.27%	86.22%	82.42%
55-60	15.32%	23.46%	15.10%	12.67%	14.44%
45-55	3.98%	12.89%	7.26%	0.64%	1.77%
40-55	1.16%	4.05%	2.61%	0.11%	0.08%
30-40	1.50%	3.75%	4.09%	0.25%	0.89%
15-30	1.64%	1.35%	10.10%	0.11%	0.40%
0-15	0.07%	0.00%	0.57%	0.00%	0.00%

During normal conditions, the PM peak period reported the lowest proportion of speeds greater than 60 mph. However, during abnormal conditions, the AM peak period experienced the lowest proportion of speeds greater than 60 mph. For this route direction, there was an inverse relationship between absolute travel rate and variability across each temporal analysis period and observation type.

I-4.3. Incident-Focused Analysis

To undertake an incident-focused analysis, I-40 westbound was selected. The analysis was performed using more detailed incident records and average travel rate data. Travel rates with an incident indicated were further categorized by the number of lanes closed (shoulder only, one, and two or more). Cumulated travel rate distributions were generated for each stage of lane closures and compared to the distribution of travel rates without any external event flags. Statistics such as the BTI and speed distribution were also tabulated for this analysis.

The mean travel rate and standard deviation of the “normal” travel rates were tabulated for each TMC segment for application as threshold for deviant observations. Travel rates for normal time/space observations were deemed deviant if more than two standard deviations above or below the mean. Deviant rates warrant future investigation for causal factors. In addition to abnormally high demand, another possible cause is spillover effects from adjacent incidents extending based the spatial extents reported to TIMS. The dataset of deviant travel rate time/space observations was cross-referenced to the incident flag dataset to identify deviate travel rates adjacent to incident flagged time/space observations.

These analyses were limited to a single facility-direction to first establish the usefulness and benefit of adding complexity to the reliability protocol. Increasing external event specificity also decreases the number of observations within each category, which may adversely impact the analysis. To mitigate issues with a smaller sample of observations, the study period can be expanded to multiple years, however, that increases the size of the analysis databases and spreadsheets. Data resolution should also depend on the monitoring system use case. Systems focusing on a single facility or facilities in a region may benefit from increased detail when developing and evaluating incident response procedures. State-level monitoring systems collecting performance data from all freeways in the state would likely become unwieldy without providing additional benefits.

CDF distributions were also generated for external event combinations for all temporal intervals. Distributions were generated for time/space observations with incidents only, weather flags only, and both an incident and weather flag Incident-only observations reported higher absolute travel times. When weather and incidents were concurrent, absolute travel rates increased but variability across the distribution of observed travel rates slightly decreased.

Exhibit I - 9 shows the CDF plots for incident only observations, Exhibit I - 10 shows the CDF plots for the weather only observations, and Exhibit I - 11 shows the CDF plots for the incident and weather observations.

Exhibit I - 9: CDF plots of incident only observations during all temporal intervals for selected I-440 EB TMC segments

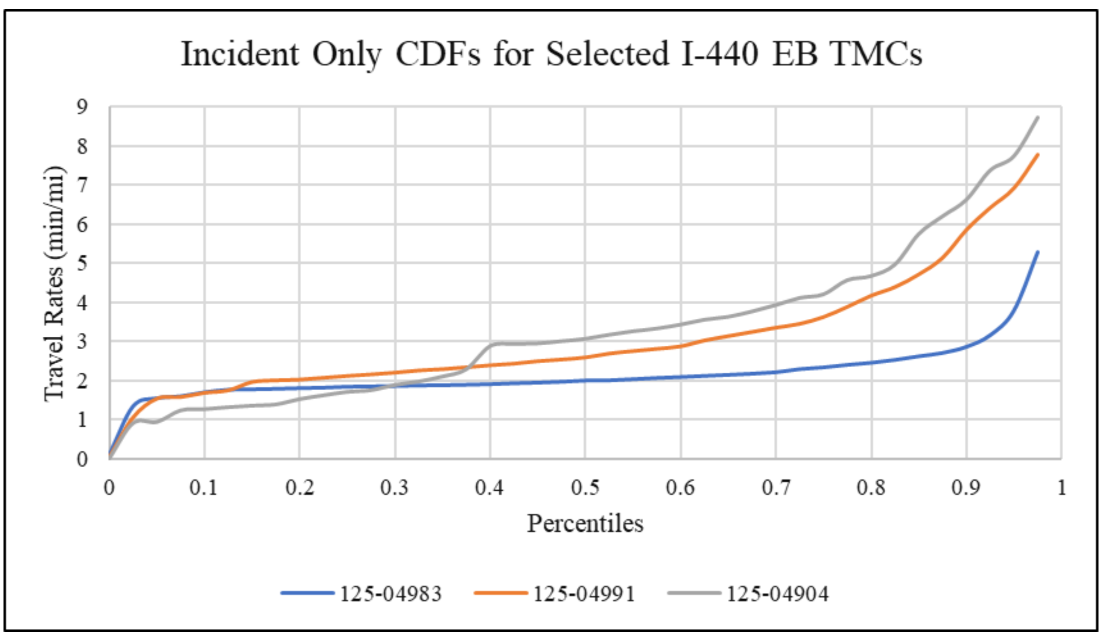


Exhibit I - 10: CDF plots of weather only observations during all temporal intervals for selected I-440 EB TMC segments

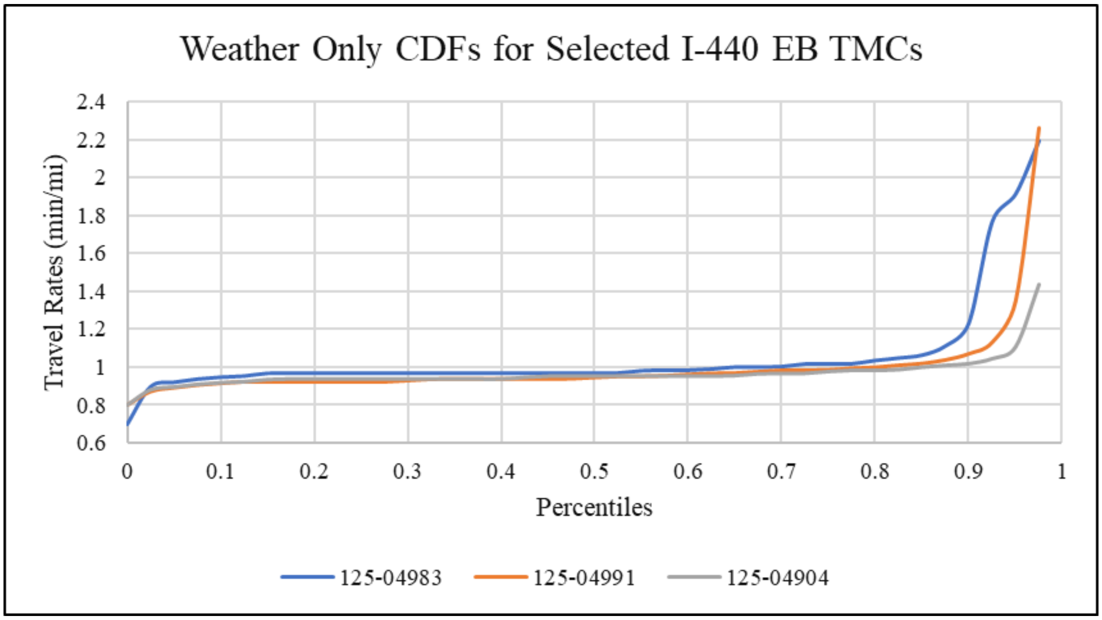
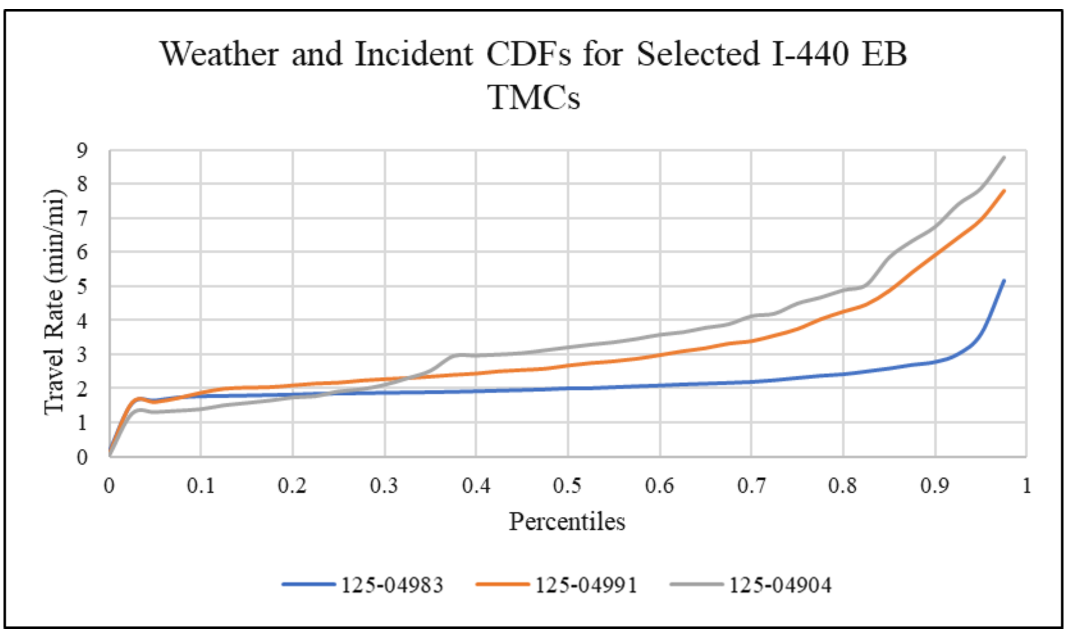


Exhibit I - 11: CDF plots of weather and incident observations during all temporal intervals for selected I-440 EB TMC segments



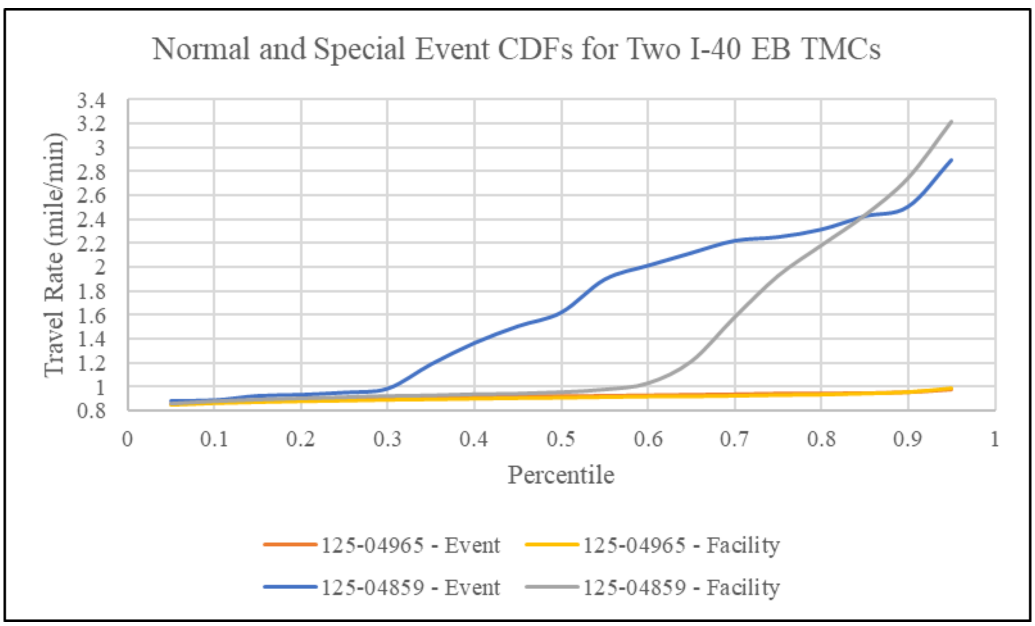
I-4.4. Special Event- Analysis

Special events are instances where the network (system) is subjected to traffic demands very different from those typically occurring. It could be that these extra demands have no significant effect as in a concert that lets out late at night. But there can be other instances where the extra demand has a significant impact, as when the event coincides with a normal peak load condition. In this instance the impacts of traffic egressing from an NC State football game at Carter-Findley Stadium was examined.

Exhibit I - 12 shows CDF plots for two TMCs in the I-40 EB event study area using the travel rates during the PM peak period on the day of the special event and travel rates from every weekday PM peak period during the 2010 study year. The PM peak period facility CDFs of 125-04859, a TMC located west of the stadium, and 125-04965, a TMC to the east of the stadium, were compared with a CDF plot based on the travel rates reported during the event temporal analysis period for each TMC. The median travel rate during the event for 125-04859 was significantly higher than the median travel rate over all weekday PM peak periods during the study year. However, the 95th percentile travel rate for all PM peaks was higher than the event-based distribution. This suggests that some users recognized the potential for delays and chose alternative routes once travel rates start drastically increasing.

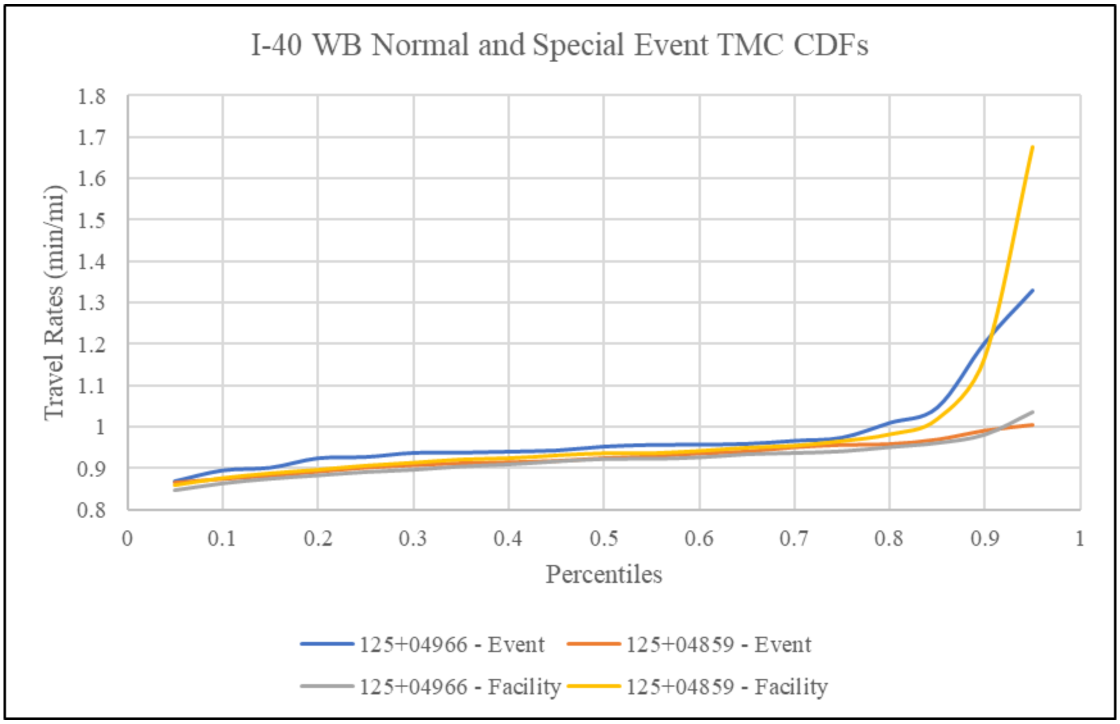
I-40 WB TMCs in the event spatial study area reported 135 deviant observations based on the PM peak period mean and standard deviation for the facility direction. 125+04965 reported the highest number of deviant observations, 25. On average, I-40 WB TMCs had a mean travel rate during the event analysis period that was 0.027 min/mi higher than the mean travel rates for all PM peak periods in 2010.

Exhibit I - 12: CDF plots for two TMCs along I-40 EB in event spatial and temporal interview



CDFs of all weekday PM peak periods and the event PM peak period were also generated for two westbound TMCs: 125+04966 and 125+04859. The plots of each distribution are shown in Exhibit I - 13. For these I-40 WB TMCs, the 95th percentile travel rate is higher for the distribution of all PM peak periods than the event peak period.

Exhibit I - 13: CDFs of selected I-40 WB TMC segments over all PM peak periods and the event analysis period.



Only one TMC along I-440 EB among the spatial segments included in the event analysis reported a deviant time/space travel rate based on the mean and standard deviation over all PM peak periods of 2010. 125N04982 reported a single deviant observation at 5:25 PM. Among I-440 EB TMCs in the event spatial analysis area, the average difference in event and PM peak period means was -0.02 mins per mile. Exhibit I-22 shows the travel rates for selected TMCs along I-440 EB. Exhibit I-32 contains descriptions and other metrics on the TMCs on I-440 EB within the event spatial areas.

Exhibit I - 14 shows CDF plots for 125N04984 and 125-04979 corresponding to event analysis period data and facility data for every PM peak weekday period in 2010. For both TMC segments, the event distribution generally had higher rates than the facility distributions based on a year's worth of data. However, the 95th percentile was higher for both facility distributions. The larger time horizon incorporated into the facility distribution may have captured significantly deviant travel rate observations above and beyond the impacts of the special event

Exhibit I - 14: CDF plots of selected I-440 EB TMCs in the event spatial area.

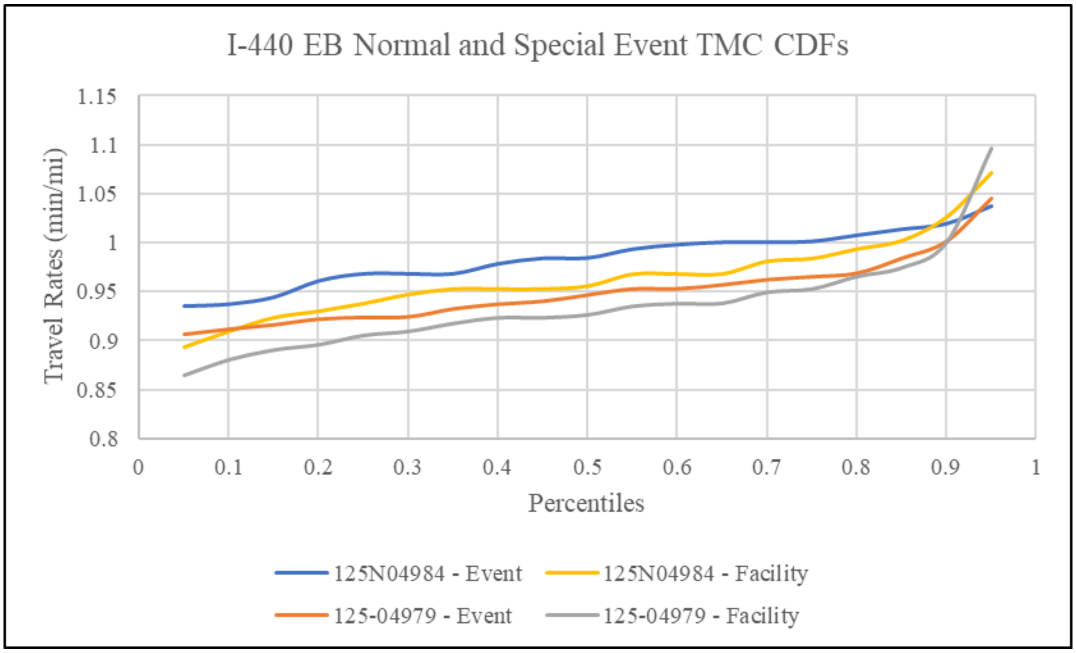
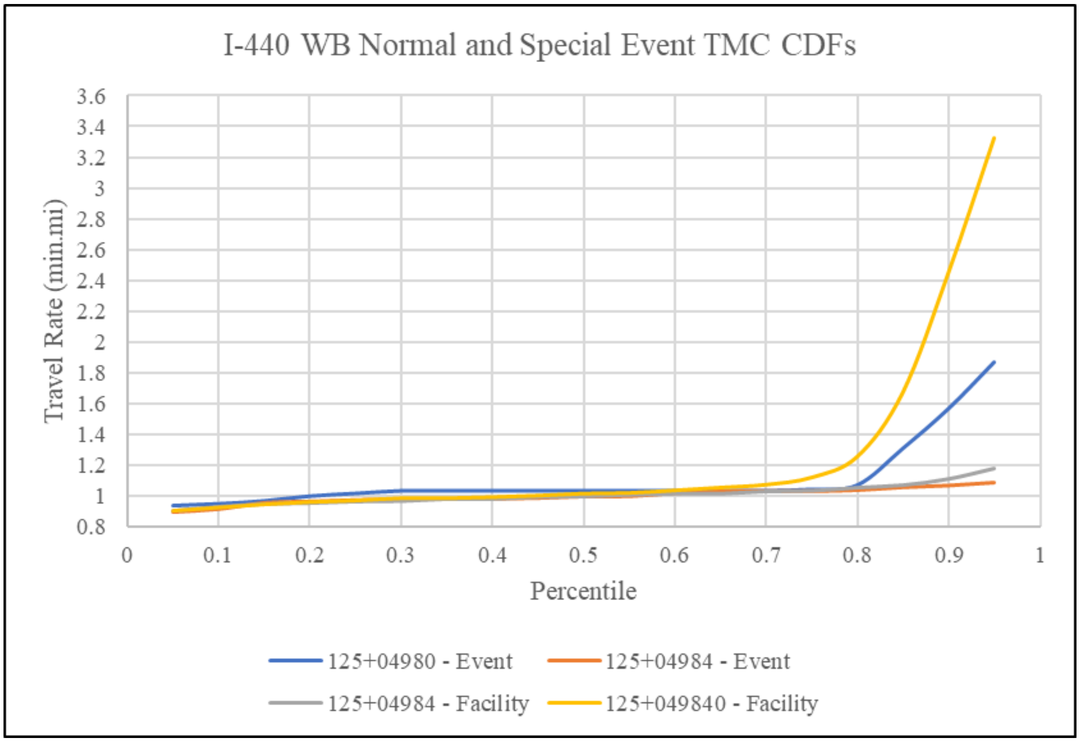


Exhibit I - 15 shows CDF plots for 125+04980 and 125+04984 for both event data during the PM peak period and PM peak periods over the entire study year. Unlike previous facility directions, the facility distributions had higher 95th percentile travel rates than the event distributions

I-440 EB and I-40 EB showed the largest impact at least qualitatively attributed to the special event. The rarity required to be designated a special demand-generating event means that reliability shouldn't necessarily be expected during such events. Therefore, analysis of these abnormal events primarily identifies time/space observations that should be classified as abnormal rather than normal.

Exhibit I - 15: CDF plots for selected I-440 WB TMCs based on event travel rates or all PM peak periods



I-5. CONCLUDING REMARKS

This report volume has described how reliability monitoring can be carried out using data sources already available to NCDOT. Data for travel rates, flow rates, weather, incidents, and special events were assembled from various sources. Preliminary data processing prepared these data for analysis. A combination of Excel and Access were used to fuse the data, create and exercise queries to extract portions of the database for analysis, and prepare exhibits.

I-5.1. Timespan of the Analysis

At first glance, an entire calendar year appears to be more than enough five-minute observational periods to generate samples of specific conditions and temporal analysis periods; however, the number of valid observations for some conditions and temporal analysis periods can be small. For most facilities, at least one of the selected TMCs did not report any observations with both an incident and weather flag. This study used peak periods four hours in length to ensure enough samples were generated. However, many facilities have shorter peak periods of only an hour and more observations would be required to develop enough samples. Longer study periods are required for more detailed external event analysis such as the number of lanes closed for incidents and specific types of national weather service warning types. Expanding the number of observations used to generate the distribution requires consideration of several factors. Increasing the duration of the study period would introduce variance in conditions from year to year. Analysis over multiple facilities should also consider distinctive characteristics about each facility/direction.

I-5.2. Metrics

Use of entire cumulative distribution functions revealed more trends than specific numerical measures such as the buffer-time index, misery-time index, and planning time index. The simple metrics may provide easier-to-understand ideas from the public's perspective, but for agency analysis, they lack the detail needed to identify mitigating actions.

I-5.3. Stitched Travel Rates

This case study converted speeds into stitched travel rates so that TMC segments of various lengths could be compared. This was critical to do so that very low travel rates in individual time intervals did not skew the results or the findings.

The route-based analyses utilize routes generated by a spatiotemporal stitching algorithm that reports route travel rates for vehicles entering the route during the original five-minute interval. Therefore, these travel times/rates are especially useful when comparing various departure windows. Results generated from the route-based analysis should be converted into public friendly units such as miles per hour and travel time in minutes, rather than travel rates or travel time indices. While not addressed in the case study, travel time reliability concepts can also be applied to major surface arterials. The constructed routes were incomplete because they didn't include US 1, a major commuting corridor that provides connectivity to I-540, I-440, and I-40 in the region. In some cases, these segments may represent the critical segments of a commuting trip on either end of the trip.

I-5.4. Data Assembly

This study identified deviant observations that weren't explained by external data collected from available sources. Operational monitoring programs should be integrated into live traffic management centers so that operators can enter notes when real-time travel times and video imagery indicates unusual conditions. Notes recorded in real time would provide invaluable information for accurately constructing travel time reliability analyses.

Input data directly impacts the quality of the analysis. Therefore, additional research on more precise data collection methods and equipment may increase the quality of the analyses produced. Given the general move away from fixed-base radar sensors, the accuracy and precision of the vehicle probe data is paramount. Where possible, alternative or backup data collection tools should be deployed to verify and calibrate the third-party speed data. As the market penetration of probe-equipped vehicles increases, methods should be evaluated to approximate facility flow rate from the probe data directly.

Weather radar data provides the most detail of any currently available data source. However, weather radar systems simply measure reflectivity in the atmosphere, from which precipitation intensities are derived into data products commonly found in weather forecasts. Additional work can be done to refine this process of identifying rainfall intensities and assigning them to spatiotemporal observations. Weather Underground (https://www.wunderground.com/) maintains a large network of small weather stations providing hyperlocal observational data such as temperature and precipitation. However, past data wasn't easily retrieved from their platform and thus was not incorporated into this study. As with other external variables, an operational monitoring system should record live or near real-time data from all available weather stations in the region adjacent to the facility. It is far easier to capture data as it is collected than to recreate datasets after the fact.

New sources of external data can also be explored to capture information about the facility and the traffic stream along it. For example, wintery events often have impacts persisting past the initial snowfall, so even when there is no precipitation occurring, the roads can still be very impacted. One possibility is to use division maintenance records to determine when a segment was salted, plowed, etc. by a transportation agency. While freeways are rarely closed for special events, police records should indicate the location and duration of street closures adjacent to freeway facilities that could affect interchange operations.

Once external event data is collected and processed, the monitoring system ultimately has to make a determination as to the impact of each event. The case study uses static external variable thresholds to define what constitutes an abnormal event condition. However, these criteria may need to be adjusted at least on a seasonal basis. For example, checking for freezing temperatures may be unnecessary during the summer months, and vice versa if there is a temperature upper bound threshold. Precipitation rates should be readjusted for wintery conditions where intensities are order of magnitudes different for rain events.

I-5.5. Analysis and Findings

At the facility-level, incidents significantly increased travel rates compared to normal conditions during all temporal analysis periods. Analyzing both directions of each facility revealed peak hour directional splits as expected by commuting patterns in the region. I-440, the only facility with significant geometric changes along the route, showed that structural overcapacity in the form of a bottleneck had a more pronounced effect on travel rates than the external events. This impact was hidden by reliability metrics based on the mean travel rates, which are inflated by recurring congestion.

I-5.6. Future Work

Little research has directly addressed the causality of reliability impacts from various external events. At best, the monitoring system simply establishes a correlation between increased travel rates and external event severity. One potential weakness of this study was the segregation of observations based on the presence of external events. While the mean and standard deviation for “normal” conditions should be tabulated from observations without any flagged variable, generating distributions of separated observations may yield additional insights into the interaction of the variables and impacts on reliability. Lastly, for most users, reliability is perceived qualitatively by users. Therefore the quantitative metrics should be reconciled to users perception of reliability to insure that the metrics collected from the monitoring system are aligned with the users’ experience. Travel time reliability will continue to shape traffic engineering processes moving forward and is worthy of additional research.

I-6. REFERENCES

1. List, G.F., B. Williams, N. Rouphail. *SHRP 2 Report S2-L02-RR-1:Establishing Monitoring Programs for Travel Time Reliability*. Transportation Research Board, Washington, D.C., 2014, DOI 10.17226/22612.

2. USDOT FHWA. National Performance Management Measures: Assessing Performance of the National Highway System, Freight Movement on the Interstate System, and Congestion Mitigation and Air Quality Improvement Program. 23 CFR Part 490, FHWA-2013-0054. *Federal Register*. Vol. 82, No. 11, 2017, pp.5970-6050.

3. I-95 Corridor Coalition, *Regional Integrated Transportation Information System (RITIS)*, http://i95coalition.org/projects/regional-integrated-transportation-information-system-ritis/

4. Chase, R.T., B.M. Williams, N.M. Rouphail, and S.Kim. Comparing Reported Travel Times between Temporally-Stitched and Simultaneous Methods at Various Aggregation Intervals. Presented at 91st Annual Meeting of the Transportation Research Board, Washington, D.C., 2012.

5. *Highway Capacity Manual, 6th Edition*, Transportation Research Board, Washington, D.C., 2016.

6. North Carolina Department of Transportation (NCDOT), North Carolina Department of Transportation, Traveler Information, TIMS, https://tims.ncdot.gov/tims/regionsummary.aspx

7. National Weather Service, Raleigh Forecast Office, https://www.weather.gov/rah/

8. Iowa Environmental Mesonet, Iowa State University, https://mesonet.agron.iastate.edu/nws/

9. State of North Carolina Climate Office, http://www.nc-climate.ncsu.edu/

10. Li, Z., L. Elefteriadou, and A. Kondyli. Quantifying Weather Impacts on Traffic Operations for Implementation into A Travel Time Reliability Model. *Transportation Letters: The International Journal of Transportation Research*, Vol. 8, No. 1, 2016, pp. 47-59.

APPENDIX I – A: ABNORMAL CONDITION ASSESSMENT

Data from external sources including incidents and weather events were analyzed to identify trends and other patterns in the data. Detailed metrics for each external variable distinguish a reliability monitoring system from predictive methods to determine travel time reliability. These external events cannot be entirely prevented. However, modifications to both geometric design and response protocols can improve reliability and should be a focus of facility operators evaluating possible reliability improvement projects. Data collection methods were also analyzed to identify possible inefficiencies in the case study monitoring system. Table I-A-1 indicates the number of TMCs and length of each facility direction.

Incident Data Summary and Analysis

Incident records stored in TIMS assigned an incident type to each incident in addition to other metrics including the number of lanes closed and duration. For each facility, the number of collisions of each type and the number of time/space regions for which a collision of such type was active. In addition, incidents were classified as either unplanned or planned. Unplanned incidents included disabled vehicles, vehicle collisions, road obstructions, vehicle fires, and other incidents lacking an incident type classification. Congestion incidents included in the data set were TIMS entries by a controller in the Traffic Management Center. Congestion records in TIMS generated automatically were not included in the incident dataset. Planned incidents included construction, maintenance, and special events.

Data	I-40 EB	I-40 WB	I-440 EB	I-440 WB	I-540 EB	I-540 WB	Wade EB	Wade WB	All
# of TMC Segments	51	51	30	30	16	16	6	6	206
Total Length (mi)	40.56	40.86	15.06	15.71	16.08	15.98	2.33	2.28	148.86

Table I-A - 22 contains aggregated incident data by facility direction. Table I-A-3 lists the number of time and space observations for which each incident type was active by each facility direction.

Table I-A - 1: Number of TMC Segments and Total Length of Each Facility Direction

Data	I-40 EB	I-40 WB	I-440 EB	I-440 WB	I-540 EB	I-540 WB	Wade EB	Wade WB	All
# of TMC Segments	51	51	30	30	16	16	6	6	206
Total Length (mi)	40.56	40.86	15.06	15.71	16.08	15.98	2.33	2.28	148.86

Table I-A - 2: Incidents Recorded in TIMS by Incident Type and Facility Direction

Incident Type	I-40 EB	I-40 WB	I-440 EB	I-440 WB	I-540 EB	I-540 WB	Wade EB	Wade WB	Total
Congestion	14	13	4	1	0	1	0	0	33
Construction	2	9	0	0	0	0	0	0	11
Disabled Vehicle	20	22	6	12	3	1	1	1	66
Fire	3	8	1	1	2	0	0	0	15
Maintenance	8	11	9	8	0	0	1	0	37
Night Time Construction	30	28	0	0	0	0	0	0	58
Other	1	1	0	0	0	0	0	0	2
Road Obstruction	2	2	1	1	0	0	0	0	6
Special Event	0	0	1	1	0	0	1	1	4
Vehicle Collision	263	196	90	116	16	0	5	1	702
Planned	40	48	10	9	0	0	2	1	110
Unplanned	303	242	102	131	21	17	6	2	824

Table I-A- 3: Number of Active Time/Space Observations by Incident Type and Facility Direction

Incident Type	I-40 EB	I-40 WB	I-440 EB	I-440 WB	I-540 EB	I-540 WB	Wade EB	Wade WB	Total
Congestion	800	717	188	10	0	39	0	0	1834
Construction	1500	6721	0	0	0	0	0	0	8221
Disabled Vehicle	95	203	47	86	36	6	12	6	491
Fire	25	55	6	12	29	0	0	0	127
Maintenance	918	12021	599	5368	0		13	0	18919
Night Time Construction	23077	17613	0	0	0	0	0	0	40690
Other	287	287	0	0	0	0	0	0	574
Road Obstruction	54	29	12	18	0	0	0	0	113
Special Event	0	0	109	109	0		150	149	517
Vehicle Collision	3345	4674	885	1795	238	307	60	0	11304
Planned	25495	36355	708	5477	0	0	163	149	68347
Unplanned	4686	5965	1138	1921	303	352	72	6	14443

During the 2010 study year, 1636 incidents were reported to and stored in the RITIS database across all facility directions in the study area. Incidents were active for 94,094 time/space observations over 206 spatial segments and 105,120 temporal observation intervals. Unplanned incidents represented 88% of all reported incidents, but only 17.45% of time/space observations included an active incident. Among unplanned incident types, vehicle collisions were the most common, representing 43% of all reported incidents. Nighttime construction was the most commonly reported planned incident type at 3.55% of reported incidents and attributed to 43% of all time/space observations with an active incident.

No planned incidents were reported along I-540 in both directions, likely attributable to its relatively recent construction. I-40 EB reported the highest number of reported incidents per TMC segment. I-440 WB reported the highest number of accidents per mile. I-40 WB had the highest number of incident active time/space observations both per TMC segment and per mile. These numbers are not adjusted for vehicle exposure. Therefore, the higher incident totals for I-40 EB and WB can likely be attributed to higher vehicle miles traveled.

NWS Warnings and Observational Weather Data

In this study, spatial resolution was prioritized over temporal resolution due to significant spatial variation of hourly precipitation intensity. The standard deviation between the reported air temperature and hourly precipitation rate for each of the five weather stations spread across the study region were tabulated for each temporal observation interval and averaged to determine the average standard deviation. Additionally, the standard deviations of temporal observations with at least two stations reporting adverse conditions (air temperature below 32° or hourly precipitation rates greater than 0.1 inch/hour) were tabulated to measure deviation from normal during critical conditions. Time/space regions with air temperatures below freezing and reported precipitation indicate the possibility of snow, sleet, freezing rain, or a wintery mix that could adversely impact facility operations. Table I-A- 4 details weather station assignment to facility directions.

Table I-A - 4: Number of TMC segments assigned to each weather station by facility direction

Facility	CLAY	LAKE	REED	KRDU	KIGX
I-40 EB	2	16	8	17	8
I-40 WB	3	16	8	17	7
I-440 EB	0	10	20	0	0
I-440 WB	0	10	20	0	0
I-540 EB	0	0	3	13	0
I-540 WB	0	0	3	13	0
Wade EB	0	0	6	0	0
Wade WB	0	0	6	0	0
TOTAL:	**5**	**52**	**74**	**60**	**15**

For all temporal observation periods reporting valid readings from at least two stations, the average air temperature standard deviation was 1.342° F. The average air temperature standard deviation of temporal intervals with at least two valid readings and one reading exceeding the adverse threshold was 1.219° F. These findings reflect low general temporal deviation of air temperature across a region. Weather station KIGX in Chapel Hill, NC reported the most five-minute temporal intervals with 8,808 periods with air temperatures lower than 32° F over the year-long study period. The weather station located in Clayton, NC reported the fewest temporal intervals with only 7,884 periods with below freezing air temperatures. The standard deviation of the number of time periods with air temperatures lower than 32° F for each weather station was 380.1 temporal periods per year.

Among all temporal observations reporting at least two valid precipitation readings greater than zero inches/hour, the average standard deviation between the five weather stations was 0.0519 inches/per. For all time intervals with at least two valid precipitation readings above the adverse threshold, 0.1 inches per hour, the average standard deviation was 0.167 inches per hour. Therefore, significant spatial variation was present in precipitation amounts across the study area. Data obtained from the weather stations were reported at an hourly temporal resolution and extrapolated to all five-minute observation periods within the applicable hour. The variation among precipitation rates averaged over the course of an hour indicates irregular spatial patterns of precipitation events. Higher spatial resolution may be needed to make accurate assessments of adverse weather conditions.

The highest number of time intervals with recorded precipitation, 10,728, were reported at the KIGX weather station. However, KIGX reported the fewest number of temporal periods with hourly precipitation rates greater than 0.25 inches per hour at 180. CLAY weather station reported the most temporal periods with hourly precipitation rates greater than 0.1 inches per hour but less than 0.25 inches per hour, 1,344. CLAY also reported the most time intervals with precipitation rates greater than 0.25 inches per hour.

The KRDU weather station reported the most temporal intervals with both an air temperature below 32° F and measurable precipitation, 786 time periods. KRDU and REED, the weather station at Reedy Creek in southwest Raleigh, both reported 24 time periods with a temperature below freezing and precipitation greater than 0.1 inch per hour. Precipitation and below freezing air temperatures were observed at no more than three stations during a single observational interval. Adverse winter weather is infrequent enough in the region that reliability during such conditions is not considered. However, regions with colder winters and more winter precipitation may place more significance on reliability during snow, sleet, freezing rain, etc.

Table I-A - 5 shows the breakdown of number of weather stations reporting air temperatures during each temporal interval. For over half of the temporal observations for which at least one reported air temperature was below freezing, all five weather stations reported air temperatures below freezing. 89.9% of all temporal observations reported no air temperatures below freezing while 6.22% of temporal observations reported air temperatures below freezing for all weather stations.

Table I-A - 5: Temporal observations with air temperature readings below freezing by number of weather stations reporting temperatures below freezing

# of Stations Reporting Adverse Conditions	Temporal observations with exact # of adverse stations	Temporal observations with at least # of adverse stations	Percentage of temporal observations with at least # of adverse stations
0	94,525		89.9%
1	1,296	10,596	10.1%
2	924	9,300	8.85%
3	864	8376	7.97%
4	972	7,512	7.15%
5	6540	6540	6.22%

All five weather stations reported no measurable precipitation for 87,685 temporal intervals, over 83.41% of all temporal intervals during the study years. Only 1,668 time periods reported at least one precipitation rate greater than 0.1 inch per hour. **Table I-A -** 6 breaks down the number of temporal observations reporting measurable precipitation rates by the number of stations reporting precipitation.

Table I-A - 7 lists the number of temporal observations with at least one reported precipitation rate greater than 0.1 inch per hour.

Table I-A - 6: Temporal Observations with reported measurable precipitation by number of stations reporting precipitation

# of Stations Reporting Adverse Conditions	Temporal observations with exact # of adverse stations	Temporal observations with at least # of adverse stations	Percentage of temporal observations with at least # of adverse stations
0	87,685		83.4%
1	7,680	17,436	7.31%
2	4,104	9,756	3.9%
3	2,076	5,652	1.97%
4	1,524	3,576	1.45%
5	2,052	2,052	1.95%

Table I-A - 7: Temporal observations with reported hourly precipitation rates greater than 0.1 inch per hour by number of stations reporting an adverse precipitation rate

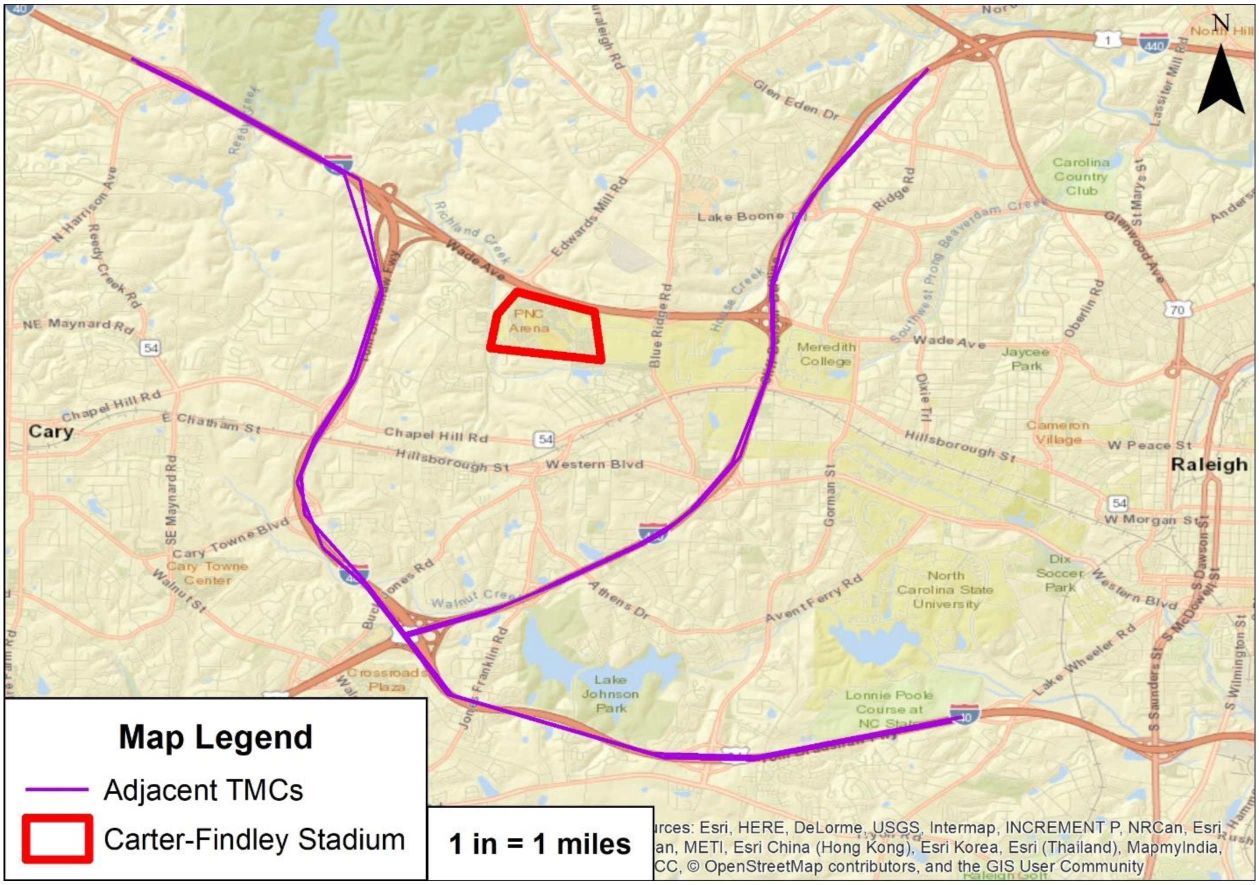
# of Stations Reporting Adverse Conditions	Temporal observations with exact # of adverse stations	Temporal observations with at least # of adverse stations	Percentage of temporal observations with at least # of adverse stations
0	101,821		96.86%
1	1,668	3,300	1.59%
2	900	1,632	0.86%
3	408	732	0.39%
4	180	324	0.17%
5	144	144	0.14%

Special Event Data

One significant special event during the 2010 study year was the Thursday-night NC State home football game held on September 16th at Carter-Finley Stadium. The game started at 7:30 PM, however, fans began arriving in the parking lots earlier in the afternoon. For the reliability analysis, the start of the event analysis period was set at 4:00 PM. The event analysis period ended at 10:00 PM. This temporal window shows the entire weekday evening peak period. The stadium is located adjacent to the Wade Avenue extension and near I-40 and I-440, therefore gameday traffic interacted with typical evening rush hour traffic and likely increased travel times near the stadium. By the end of the game, background traffic was likely significantly lower and departing fans were more easily absorbed into the freeway traffic streams.

Exhibit I-A - 1 indicates the location of the stadium and adjacent TMC segments that were analyzed to determine possible impacts on facility direction and commuting routes.

Exhibit I-A - 1: Location of football stadium and TMCs included in the event analysis.



Determination of which public events occurring during the study year constitute special demand-generating events was the responsibility of the analyst based on the purpose and objectives of the analysis and local knowledge about such events and adjacent facilities. Other mass-gathering events occurred during the 2010 study year, however, adjacent facilities can typically handle the additional demand. Congestion may be present but limited to local streets used to access the venue.

Wade Avenue was not included in the analysis because this facility primarily provides access to the stadium, adjacent arena, and state fairgrounds. Commuters that typically utilize the Wade Avenue extension on weekday evenings likely chose alternative routes to avoid gameday traffic. However, I-40 and I-440 continued to serve commuter traffic and were susceptible to major impacts on the traffic stream. A spatial selection was performed in GIS to develop a list of TMC segments in the immediate vicinity of the stadium that could have outsized traffic demand due to the football game. Traffic along US 1 south of I-440 was also likely impacted, however, that facility was not among those in this study.

Twelve TMC segments were identified as likely impacted for both directions of I-40 and 13 TMC segments were identified for both directions of I-440. Travel rate data, deviant time/space observations, means, and percentile data were retrieved from the facility direction datasets. Deviant time/space regions without associated external events as defined by the facility PM peak period mean and standard deviation were identified for each TMC during the event temporal analysis period. Travel rates without any external event flags were classified as deviant if outside of two standard deviations on either side of the mean. While the last two hours of the event analysis period were outside of the facility PM peak period, the PM means and standard deviations for each TMC segment were used for all time intervals.

I-40 EB TMCs located near the stadium reported 68 normal deviant observations during the event temporal analysis period. 125-04859 and 125N04859 both reported the highest number of deviant five-minute temporal intervals at 12. 9.87 miles of I-40 EB was included in the event analysis area, the longest of any facility direction in the vicinity of the stadium. The mean travel rates were tabulated for each TMC from 4:00 PM to 8:00 PM on the day of the event and compared to the PM peak facility means for the entire year. On average TMC means during the special events were 0.076 minutes per mile higher than the PM peak facility mean. The highest increase, 0.242 minutes per mile, occurred along the 125N04859 segment. The difference in means for each I-40 EB TMC segment was less than one standard deviation.

Exhibit I-A - 2 plots 5-minute aggregated travel rates over the event temporal analysis period for several I-40 EB TMC segments, namely 125N04860, 125-04859, 125-04857,125N04857, 125-04965, and 125N04965. Table I-A- 8 contains information about the TMC segments along I-40 EB near the stadium.

Exhibit I-A - 2: Travel Rates for selected I-40 EB TMC segments during special event

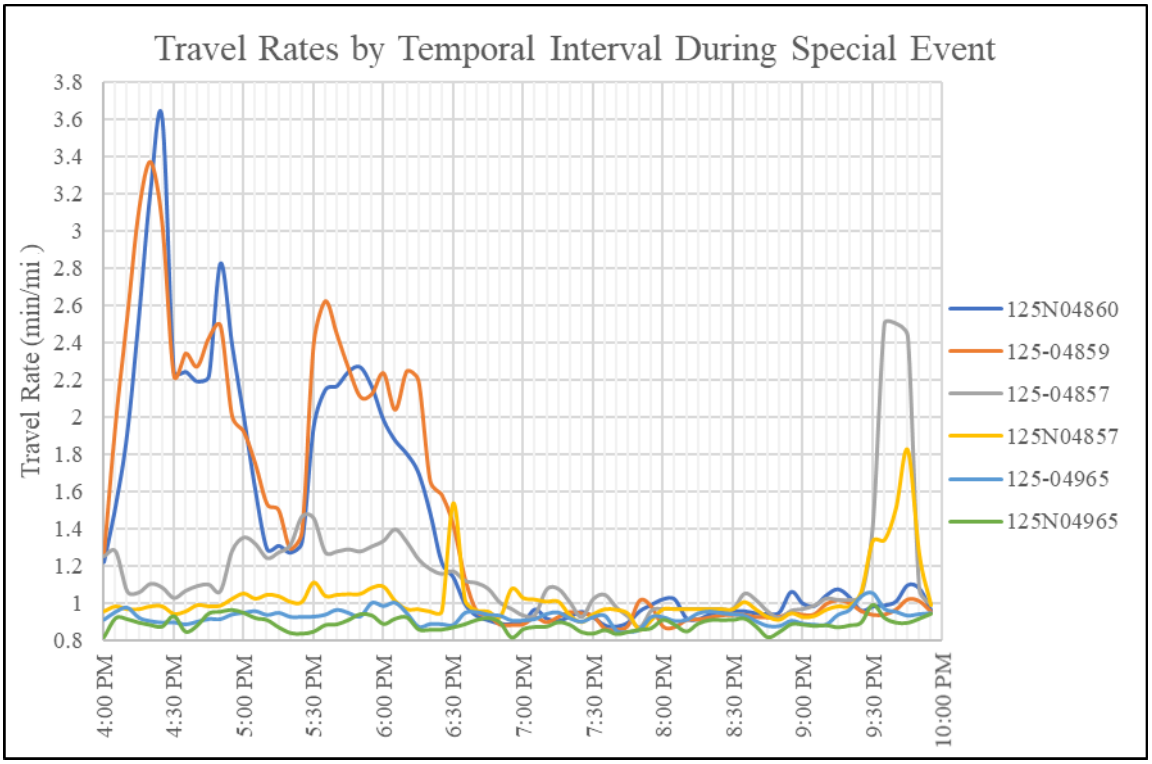


Table I-A- 8: Description of TMC segments along I-40 EB included in the event study area

TMC Segment	Nearest Interchange	Length (miles)	Mean Event PM Peak Travel Rate	Number of Deviant Intervals
125N04860	Harrison Ave	0.548	1.5965	6
125-04859	Wade Ave Ext	1.083	1.6997	12
125N04859	Wade Ave Ext	1.063	1.6129	12
125-04858	NC-54 / Cary	0.783	1.4310	6
125N04858	NC-54 / Cary	0.519	1.4654	10
125-04857	Cary Town Blvd	0.378	1.1480	3
125N04857	Cary Town Blvd	0.571	1.0039	1
125-04856	I-440/US 1 / 64	0.402	0.9812	2
125N04856	I-440/US 1 / 64	1.064	1.0345	8
125-04965	Gorman St.	1.531	0.9213	0
125N04965	Gorman St.	0.598	0.8992	0
125-04964	Lake Wheeler Rd.	1.332	0.8849	0
TOTALS:		**9.87335**		**68**

APPENDIX I – B: DETAILED RESULTS FROM THE RELIABILITY ASSESSMENTS

Facility-Level Travel Time Reliability Analysis

Transportation agencies generally view the roadway network through the prism of individual facilities and directions. Performance metrics are often spatially categorized by facility and direction. Facility and direction are also common jargon used to describe a location along a road. Therefore, a travel time reliability monitoring system should have the capability to analyze reliability within a facility direction spatial context. This study performs TMC-level analysis by facility direction. Route-level analysis is reported independently. Eight facility-direction pairs were identified within the Research Triangle region, namely I-40 WB, I-40 EB, I-440 WB, I-440 EB, I-540 WB, I-540 EB, Wade Ave Ext. WB, and Wade Ave Ext. EB.

All facilities except both directions of I-540 follow conventional TMC segmentation. Eastbound TMC segments contain a "-"or "N" in the name of the segment. Westbound TMC segments have a "+" or "P". I-540 segmentation is reversed, i.e. plus and P TMC segmentation are eastbound. Plus and minus TMCs are generally between interchanges, N or P TMCs are located within interchanges. TMC segmentation data was obtained directly from the output files of the RITIS database.

Three TMC segments spatially distributed along I-40 WB and I-40 EB were selected to display CDF plots and tabulated data in this report, data for the remaining TMCs were provided in an Appendix. Two TMC segments were selected for each direction of I-440 and I-540. One TMC segment was designed for each direction of the Wade Avenue Extension.

For each TMC segment included in the report analysis, external variables were further summarized by facility direction and sub grouped by time of day analysis periods, i.e. 24-hours, AM, PM, and weekends. Missing time/space travel rate observations were tabulated for each TMC and temporal analysis period. Stitched travel rates were used to generate a distribution of average vehicle speeds. Time/space observations were deemed to be normal if none of the external events were flagged and abnormal otherwise. Cumulative distribution functions were developed for normal and abnormal observations as defined by the absence of external events for each time of day analysis period. Additionally, CDFs were generated for weather, incidents, and weather plus incident observations. The buffer time index was also tabulated for each scenario. All TMC segments for each facility direction were ranked by buffer time index for the AM peak period, PM peak period, weekends, and 24-hour analysis periods.

I-40 Eastbound Facility Analysis

Of 50 TMC segments along I-40 EB within the study area, I25-04870, 125-04857, and 125N04836 are highlighted in more detail. 125-04870 is a three-lane segment adjacent to the NC 751 interchange in western Durham County at exit 274, 125-04857 has three through lanes and is located near the Cary Towne Blvd / Farm Gate Rd. at exit 2910. 125N04836, a two-lane segment, is located at the US 70 Business interchange in southwestern Wake County. Table I-B - 1 contains summary data for each of the highlighted TMC segments. Table I-B - 2 lists data on external events during the study year.

Table I-B - 1: Description of selected TMC segments along I-40 EB

	125-04870	125-04857	125N04836
Number of Lanes	3	3	2
Length (mi)	0.9495	0.3782	0.7516
Nearest Interchange	NC 751	Cary Towne Blvd.	US 70 Business
County	Durham	Wake	Wake
Number of Invalid Time/Space Travel Rates	1,721	1,682	1,684
Median Travel Rate (min/mi)	0.9193	1.0086	0.9592
Buffer Time Index	0.0611	0.3303	0.1346

Table I-B - 2: Temporal intervals with external factors for I-40 EB selected TMCs

	125-04870	125-04857	125N04836
Temporal intervals with deviant travel rates			
24-hour	1,823	3,268	3,106
AM Peak Period	424	501	298
PM Peak Period	152	220	4
Weekends	283	240	28
Temporal intervals with an active unplanned incident			
24-hour	57	40	63
AM Peak Period	32	9	0
PM Peak Period	16	18	40
Weekends	0	0	4
Temporal intervals with an active planned incident			
24-hour	181	0	0
AM Peak Period	0	0	0
PM Peak Period	0	0	0
Weekends	181	0	0
Temporal intervals with an active weather event			
24-hour	10,751	11,645	10,658
AM Peak Period	0	122	99
PM Peak Period	0	2	2
Weekends	3415	3800	3545
Temporal intervals with oversaturated flow rates			
24-hour	6	0	0
AM Peak Period	0	0	0
PM Peak Period	0	0	0
Weekends	1	0	0

Table I-B - 3 shows the speed distribution for 125-04870, 125-04857, 125N04836, and all I-40 EB TMCs. Distributions were generated for all temporal analysis periods and speeds are in miles per hour. Ranges are exclusive of the lower end of the range. 125-04857 reported significant variation, especially during the PM peak period. Only about 30% of reported travel speeds were greater than 60 mph during that temporal analysis period. 125-04870 had the highest number of reported travel speeds greater than 60 mph for all temporal analysis periods, likely due to the lane addition just upstream of this TMC segment. In general, more variation was observed during the PM peak period than the AM peak period.

Table I-B - 3: Travel speed distributions for the entire facility and three selected TMC segments over all temporal analysis periods

	125-04870	125-04857	125N04836	Facility
24-hour (all times)				
60+	97.51%	72.29%	93.94%	92.19%
55 - 60	1.53%	15.09%	2.07%	3.82%
45 - 55	0.43%	8.46%	1.09%	1.57%
40 - 45	0.10%	1.55%	0.47%	0.42%
30 – 40	0.15%	1.04%	1.12%	0.73%
15 - 30	0.16%	1.17%	1.12%	0.97%
0 - 15	0.12%	0.41%	0.20%	0.29%
AM Peak Period				
60+	96.73%	78.88%	98.75%	95.37%
55 - 60	1.20%	15.68%	1.03%	2.85%
45 - 55	0.43%	3.51%	0.17%	0.89%
40 - 45	0.19%	0.46%	0.02%	0.19%
30 – 40	0.39%	0.62%	0.01%	0.26%
15 - 30	0.63%	0.57%	0.01%	0.28%
0 - 15	0.43%	0.28%	0.02%	0.15%
PM Peak Period				
60+	96.17%	29.75%	72.77%	77.85%
55 - 60	2.29%	25.57%	4.63%	6.59%
45 - 55	0.63%	32.68%	4.81%	4.62%
40 - 45	0.11%	7.26%	2.78%	1.63%
30 – 40	0.19%	3.07%	6.76%	3.33%
15 - 30	0.32%	1.40%	7.06%	4.90%
0 - 15	0.29%	0.27%	1.19%	1.08%
Weekday Off Peak				
60+	97.56%	83.02%	96.65%	94.97%
55 - 60	1.45%	9.55%	2.15%	2.99%
45 - 55	0.56%	4.96%	0.61%	1.02%
40 - 45	0.15%	0.50%	0.12%	0.26%
30 – 40	0.15%	0.53%	0.22%	0.32%
15 - 30	0.07%	1.17%	0.21%	0.30%
0 - 15	0.06%	0.27%	0.04%	0.14%
Weekend (Sat. / Sun.)				
60+	97.33%	81.90%	96.81%	94.54%
55 - 60	1.54%	10.46%	1.91%	3.17%
45 - 55	0.64%	5.15%	0.72%	1.17%
40 - 45	0.15%	0.57%	0.11%	0.29%
30 – 40	0.20%	0.67%	0.27%	0.39%
15 - 30	0.09%	1.03%	0.16%	0.31%
0 - 15	0.04%	0.22%	0.03%	0.12%

Table I-B - 4 shows key percentile values and buffer time index tabulated for each selected TMC for all normal and abnormal observations. 125-04870 reported the lowest buffer time index and 125-04857 the highest. Exhibit I-B - 1 shows normal observation CDF plots for all three TMCs over the 24-hour analysis period. Exhibit I-B - 2: CDF plots of abnormal observations during all time intervals for selected I-40 EB TMC segments displays abnormal observation CDF plots for the selected TMCs for all temporal intervals. As indicated by the buffer time index, 125-04857 experienced significant variation beyond the 60th percentile. 125-04870 maintained near free-flow travel rates until the 90th percentile. For all time intervals, 125-04870, 125-04857, and 125N04836 reported the 48th, 8th, 21st highest buffer time index among the 50 TMC segments. 125-04859, located near the I-40 and Wade Avenue Extension interchange, had the highest buffer time index at 1.4336.

During abnormal operating conditions, percentile travel rates were slightly higher for 125-04870, however, 125-04857 and 125N04836 reported lower travel rates and buffer time indices during abnormal operating conditions. This contradiction could be the result of decreased demand during severe weather, different incident severities, and geometric design variation along the facility. Out of 50 TMC segments along I-40 EB, 125-04870, 125-04857, and 125N04836 experienced the 45th, 9th, and 40th highest buffer time index for abnormal conditions.

Table I-B - 4: Key percentiles and buffer time index of normal travel rates for selected I-40 EB TMCs for the 24-hour analysis period

	125-04870	125-04857	125N04836
Normal Percentiles			
0.05	0.8385	0.8799	0.8428
0.25	0.8824	0.9231	0.8885
0.5	0.9165	0.9434	0.9228
0.75	0.9234	1.0	0.9330
0.95	0.9725	1.2550	1.0471
Buffer Time Index	0.0611	0.3303	0.1346
Mean Travel Rate	0.9193	1.0086	0.9592
Standard Deviation	0.2442	0.3812	0.4056
Abnormal Percentiles			
0.05	0.8386	0.8798	0.8383
0.25	0.8893	0.9231	0.8899
0.5	0.9231	0.9375	0.9231
0.75	0.9257	0.9836	0.9331
0.95	0.9992	1.1538	1.0343
Buffer Time Index	0.0824	0.2310	0.1205

Exhibit I-B - 1: CDF plots of normal travel rates for selected I-40 EB TMC segments over all time periods

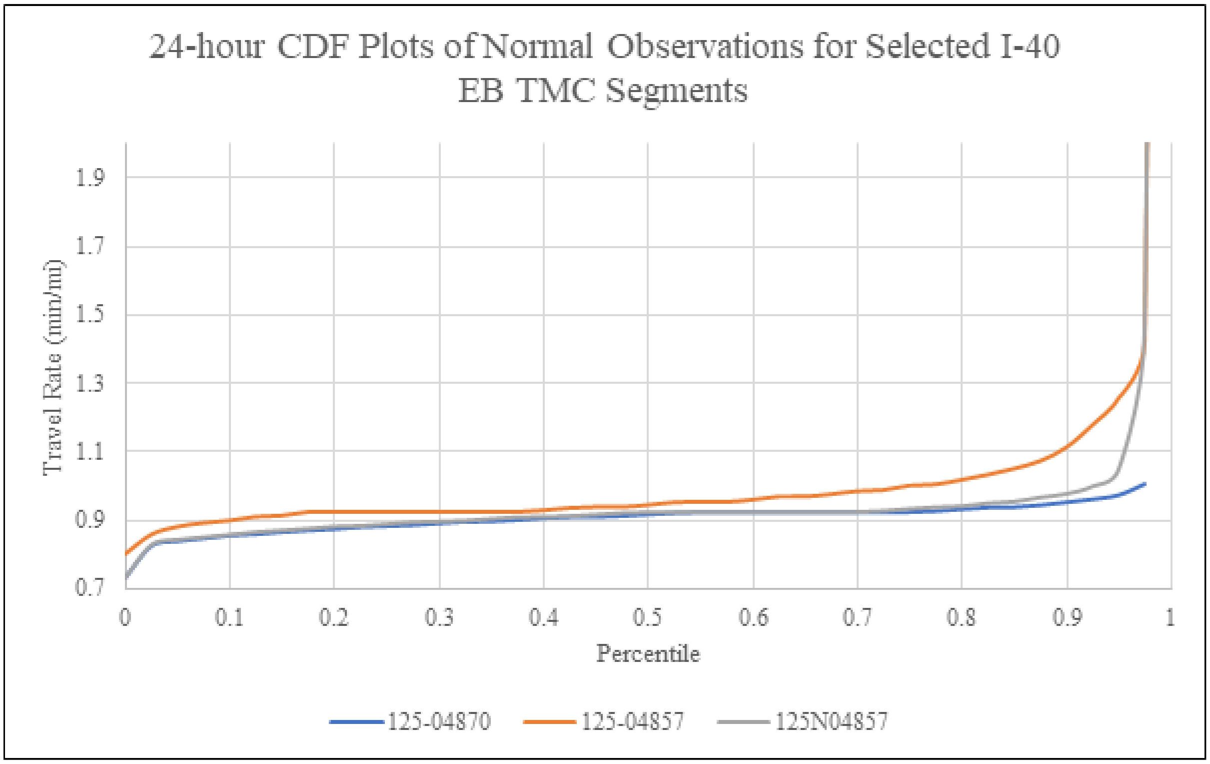
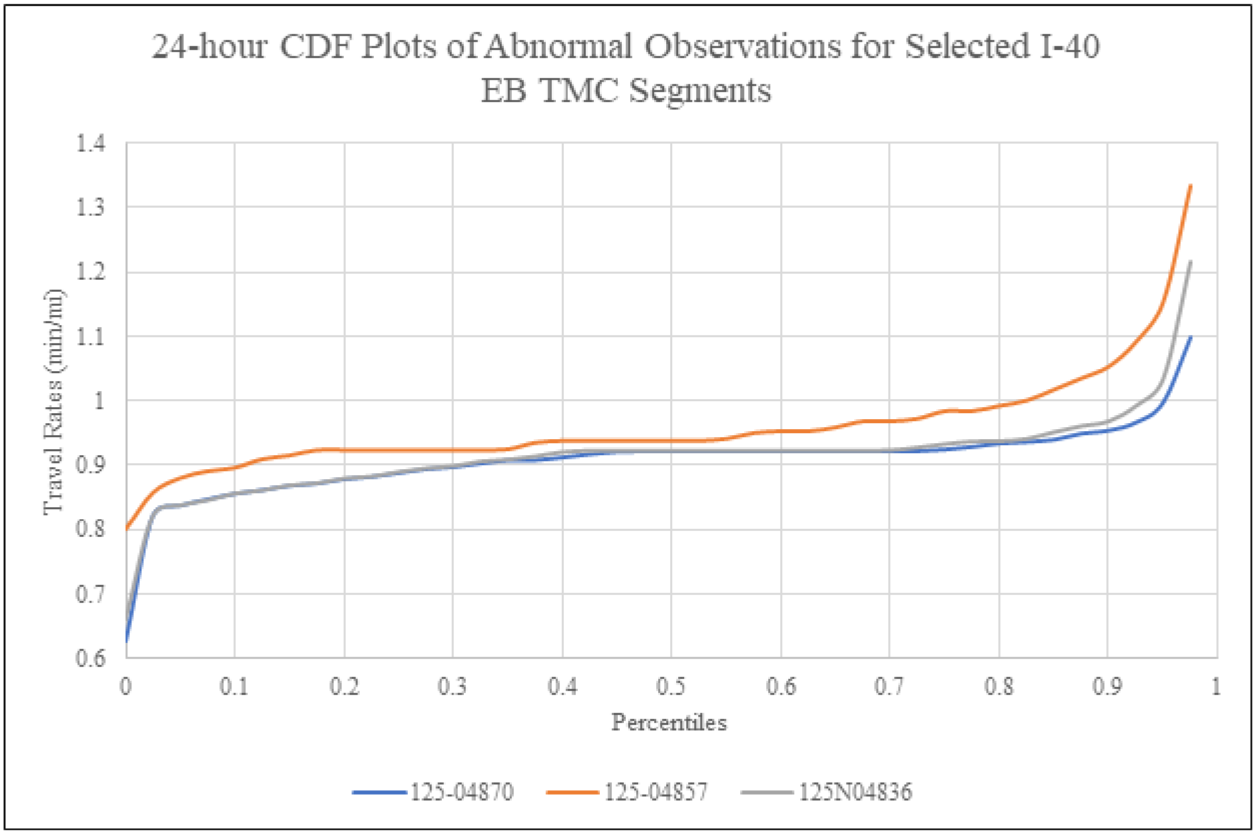


Exhibit I-B - 2: CDF plots of abnormal observations during all time intervals for selected I-40 EB TMC segments

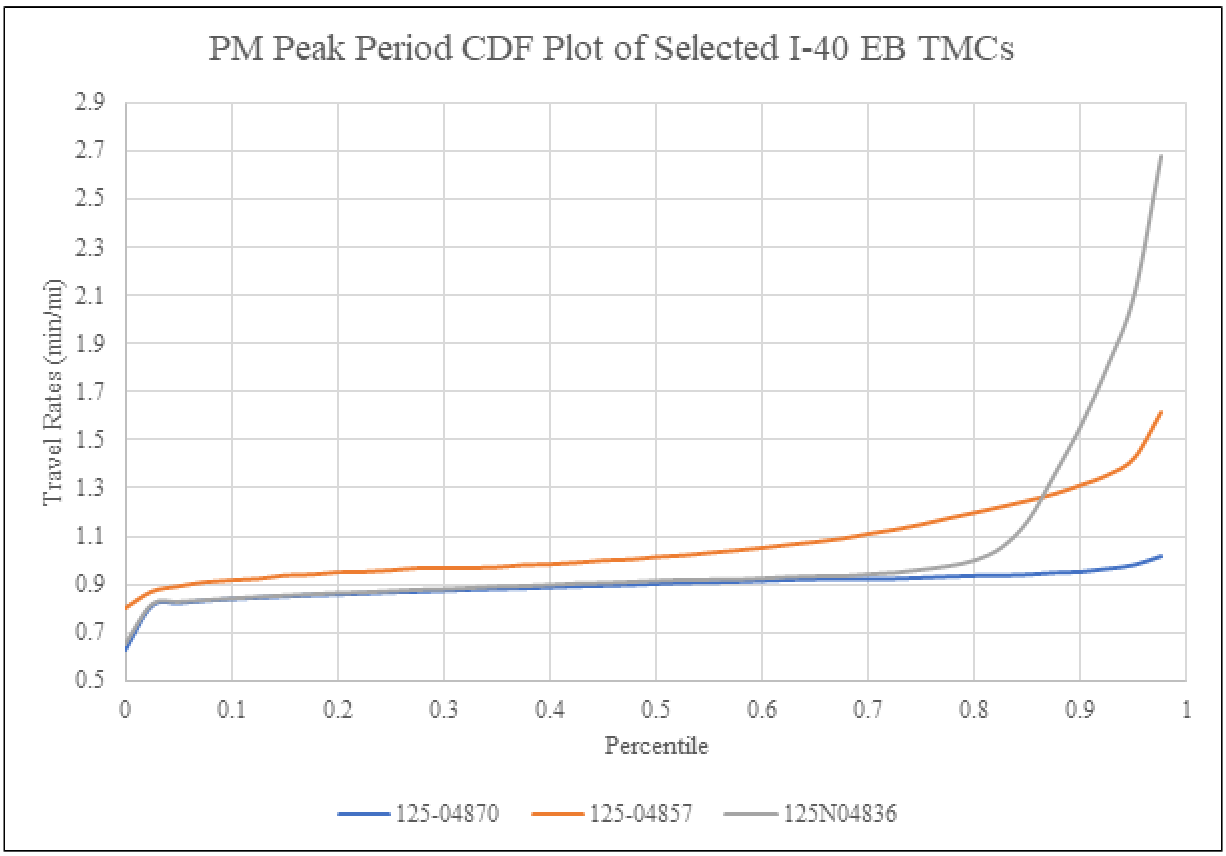


The PM peak hour was the worst performing temporal analysis period for each of the TMCs as indicated by the speed distributions. Table I-B - 5 contains critical percentiles and the buffer time index for normal travel rate observations during the PM peak period. Exhibit I-B - 3 shows CDF plots for normal and abnormal observations during the PM peak period. Out of 50 TMC segments along I-40 EB, 125-04870, 125-04857, and 125N04836 experienced the 44th, 23rd, and 12th highest buffer time index for the PM peak period. 125N04862, near the Airport Blvd. interchange at Exit 284, reported the highest buffer time index during the PM Peak period at 3.1482. A traveler would need to allow triple the median travel time to achieve a 95% on-time arrival rate.

Table I-B - 5: Key percentiles for normal and abnormal travel rate observations of selected I-40 EB TMC segments during the PM peak period

	125-04870	125-04857	125N04836
Percentiles			
0.05	0.8242	0.8916	0.8317
0.25	0.8684	0.9585	0.8761
0.5	0.9032	1.0144	0.9187
0.75	0.9285	1.1507	0.9653
0.95	0.9815	1.4296	2.1106
Buffer Time Index	0.0867	0.4093	1.2975
Mean Travel Rate	0.9179	1.0947	1.0889
Standard Deviation	0.2791	0.3301	0.6032

Exhibit I-B - 3: CDF plots of normal travel rates for selected I-40 EB TMC segments during the PM peak period.



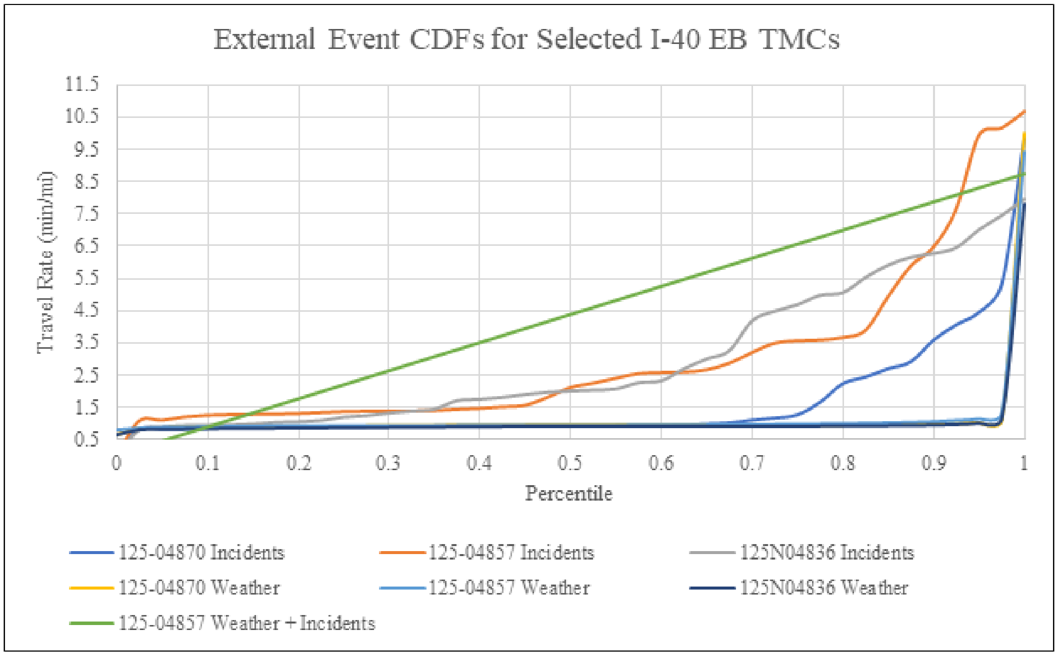
Distributions were also generated for various combinations of external events over all time intervals. External events were broken down into incidents only, weather only, and incident plus weather. Table I-B - 6 shows critical percentiles and metrics for the incident only distribution. The buffer time index for travel rates observed during active incidents was over ten times greater than the buffer time index based on the 24-hour normal observations. Incidents significantly impact travel rates at the TMC segment level. Out of 50 TMC segments along I-40 EB, 125-04870, 125-04857, and 125N04836 reported the 13th, 14th, and 23rd highest buffer time index for incident only conditions. Immediately downstream of 125-04870, segment 125N04870 experienced the highest buffer time index among the 50 segments with a buffer time index of 9.3529. Travel rates during temporal intervals with only an active weather event were more in line with normal operating conditions. Exhibit I-B - 4 displays CDF plots of external factor travel rate distribution for all time intervals.

Out of 50 TMC segments along I-40 EB, 125-04870, 125-04857, and 125N04836 were the 46th, 7th, and 39th highest buffer time index for weather-only conditions. 125N04859, near the Wade Avenue interchange, reported the highest buffer time index of 0.4169. Observations that flagged both an incident and significant weather event, i.e. below freezing, more than 0.1 inch/hour rain, or a national weather service warning were very limited. This may be attributable to data collection issues during such weather events or a high weather event threshold. Only data for 125-04857 was included in Table I-B- 17 for the combined incident and weather condition.

Table I-B - 6: Key percentiles of travel rates (min/mi) during active incidents only, for selected I-40 EB TMC segments over all time intervals.

	125-04870	125-04857	125N04836
Incidents Only			
0.05	0.8333	1.0909	0.8783
0.25	0.9002	1.3563	1.1816
0.5	0.9237	2.1033	1.9939
0.75	1.1706	3.5547	4.6745
0.95	4.4497	9.9396	7.0008
Buffer Time Index	3.8171	3.7256	2.5111
Weather Only			
0.05	0.8416	0.8792	0.8385
0.25	0.8945	0.9231	0.8899
0.5	0.9231	0.9375	0.9231
0.75	0.9264	0.9809	0.9319
0.95	0.9985	1.1450	1.0251
Buffer Time Index	0.0818	0.2214	0.1105
Incident and Weather			
0.05	N/A	0.4381	N/A
0.25	N/A	2.1903	N/A
0.5	N/A	4.3807	N/A
0.75	N/A	6.5710	N/A
0.95	N/A	8.3232	N/A
Buffer Time Index	N/A	0.9000	N/A

Exhibit I-B - 4: CDF plots of external event operating conditions during all time intervals for selected I-40 EB TMC segments.



I-40 Westbound Facility Analysis

Detailed analysis for three TMC segments selected from 51 TMC segments along I-40 WB within the study region is included in this section. 125+04837 is a three-lane segment located near Jones Sausage Rd. in southwestern Wake County at Exit 303. 125+04857 has a three-lane cross-section and is located adjacent to the Cary Town Blvd. and Farm Gate Rd. interchange at Exit 291. 125P04871, a three-lane segment, is located near the NC 54 interchange at Exit 273 near the Durham/Orange county line. Table I-B - 7 shows summary metrics and details for the selected TMC segments. Table I-B - 8 reports statistical data on the frequency of external factor events along I-40 WB.

Table I-B - 7: Description of selected TMC segments for I-40 WB

	125+04837	125+04857	125P04871
Number of Lanes	3	3	2
Length (mi)	1.3324	0.6841	0.5385
Nearest Interchange	NC 54	Cary Towne Blvd.	Jones Sausage Rd.
County	Durham	Wake	Wake
Number of Invalid Time/Space Travel Rates	1,694	1,683	1,682
Mean Travel Rate (min/mi)	0.9025	1.0758	0.9190
Buffer Time Index	0.0673	0.1017	0.052

Table I-B - 8: Frequency of external factor events for the entire facility and three selected TMC segments

	125+04837	125+04857	125P04871
Temporal intervals with deviant travel rates			
24-hour	1390	7838	2186
AM Peak Period	324	554	299
PM Peak Period	224	3104	1876
Weekends	842	4180	11
Temporal intervals with an active unplanned incident			
24-hour	21	278	64
AM Peak Period	21	186	11
PM Peak Period	0	58	49
Weekends	0	4	0
Temporal intervals with an active planned incident			
24-hour	0	100	181
AM Peak Period	0	1	0
PM Peak Period	0	0	0
Weekends	0	0	181
Temporal intervals with an active weather event			
24-hour	10658	11645	10751
AM Peak Period	1636	1752	1497
PM Peak Period	639	743	787
Weekends	3545	3800	3415
Temporal intervals with oversaturated flow rates			
24-hour	1	0	0
AM Peak Period	1	0	0
PM Peak Period	0	0	0
Weekends	0	0	0

Table I-B - 9 lists the speed distributions for the three TMC segments highlighted and facility wide for all temporal analysis periods. Ranges are exclusive of the lower end of the speed ranges. Facility wide, the AM peak period experienced greater travel time variation, however, higher variation was observed along 125N04836 during the PM peak period. 125+04857 was the most heavily impacted of the highlighted segments during the AM peak period, when only 40% of temporal intervals had average speeds above 60 miles per hour.

Table I-B - 9: Travel speed distributions for the entire and three selected TMC segments over all temporal analysis periods for I-40 WB

	125+04837	125+04857	125P04871	Facility
24-hour (all times)				
60+	97.58%	83.91%	96.69%	93.87%
55 - 60	1.32%	6.45%	2.18%	3.21%
45 - 55	0.56%	2.24%	0.60%	1.19%
40 - 45	0.17%	0.71%	0.12%	0.33%
30 – 40	0.24%	1.83%	0.16%	0.49%
15 - 30	0.11%	4.19%	0.19%	0.65%
0 - 15	0.03%	0.67%	0.06%	0.26%
AM Peak Period				
60+	90.68%	39.90%	96.82%	86.56%
55 - 60	2.91%	9.91%	2.36%	4.24%
45 - 55	2.83%	5.15%	0.64%	2.93%
40 - 45	0.95%	2.24%	0.09%	1.02%
30 – 40	1.57%	10.26%	0.08%	1.67%
15 - 30	0.85%	29.27%	0.01%	2.64%
0 - 15	0.21%	3.27%	0.00%	0.94%
PM Peak Period				
60+	99.32%	85.97%	93.71%	91.67%
55 - 60	0.54%	8.03%	3.13%	3.88%
45 - 55	0.09%	2.39%	1.33%	1.71%
40 - 45	0.02%	0.71%	0.23%	0.47%
30 – 40	0.01%	1.09%	0.41%	0.83%
15 - 30	0.01%	1.33%	0.90%	1.04%
0 - 15	0.01%	0.48%	0.29%	0.40%
Weekday Off Peak				
60+	98.64%	89.40%	97.65%	95.66%
55 - 60	1.17%	6.46%	1.83%	2.95%
45 - 55	0.15%	1.91%	0.28%	0.72%
40 - 45	0.02%	0.39%	0.04%	0.12%
30 – 40	0.01%	0.70%	0.09%	0.18%
15 - 30	0.01%	0.84%	0.08%	0.24%
0 - 15	0.01%	0.31%	0.02%	0.13%
Weekend (Sat. / Sun.)				
60+	97.76%	91.92%	96.49%	95.08%
55 - 60	1.36%	4.50%	2.28%	2.94%
45 - 55	0.53%	1.56%	0.71%	0.99%
40 - 45	0.16%	0.51%	0.21%	0.29%
30 – 40	0.17%	0.57%	0.19%	0.32%
15 - 30	0.02%	0.65%	0.07%	0.26%
0 - 15	0.00%	0.28%	0.04%	0.12%

Table I-B - 10 lists key percentile values and buffer time index values for each highlighted TMC segment for all normal and abnormal observations. All three TMC segments reported higher buffer time indices during abnormal conditions. 125+04857 experienced the highest mean travel rate and standard deviation, which was approximately half of the mean travel rate. 125+04837, 125-04857, and 125P04871 had the 42nd, 2nd, and 40th highest buffer time index among the 51 TMC segments along I-40 WB. Immediately upstream of I25+04857, 125P04856 reported the highest buffer index time for normal observations. For abnormal travel rate observations, the selected TMCs experienced the 28th, 2nd, and 44th highest buffer time indices respectively. 125P04996 reported the highest buffer index time for abnormal observations.

Table I-B - 10: Key percentiles and buffer time index of normal travel rates for selected I-40 WB TMCs for all temporal intervals

	125+04837	125+04857	125P04871
Normal Observation Percentiles			
0.05	0.8296	0.8677	0.8383
0.25	0.8696	0.9171	0.8850
0.5	0.9046	0.9244	0.9231
0.75	0.9231	0.9613	0.9375
0.95	0.9655	1.6528	0.9868
Buffer Time Index	0.0673	0.7880	0.0691
Mean Travel Rate	0.9025	1.0758	0.9190
Standard Deviation	0.0998	0.5690	0.1405
Abnormal Observation Percentiles			
0.05	0.8368	0.8779	0.8451
0.25	0.8853	0.9231	0.8983
0.5	0.9231	0.9250	0.9231
0.75	0.9242	0.9677	0.9375
0.95	1.0526	2.2408	1.0095
Buffer Time Index	0.1404	1.4225	0.0936

Exhibit I-B - 5 displays CDF plots of 24-hour normal observation for each selected TMC segment. Exhibit I-B - 6 shows CDF plots for abnormal conditions during any time interval for the selected TMC segments. Similar percentile and buffer time index trends were observed for both normal and abnormal operating conditions. This is likely due to broadly prevailing low demand such that most observations flagged as abnormal due to an external event actually experienced little or no traffic flow impacts.

Exhibit I-B - 5: CDF plots of normal travel rates for selected I-40 WB TMC segments for all temporal intervals

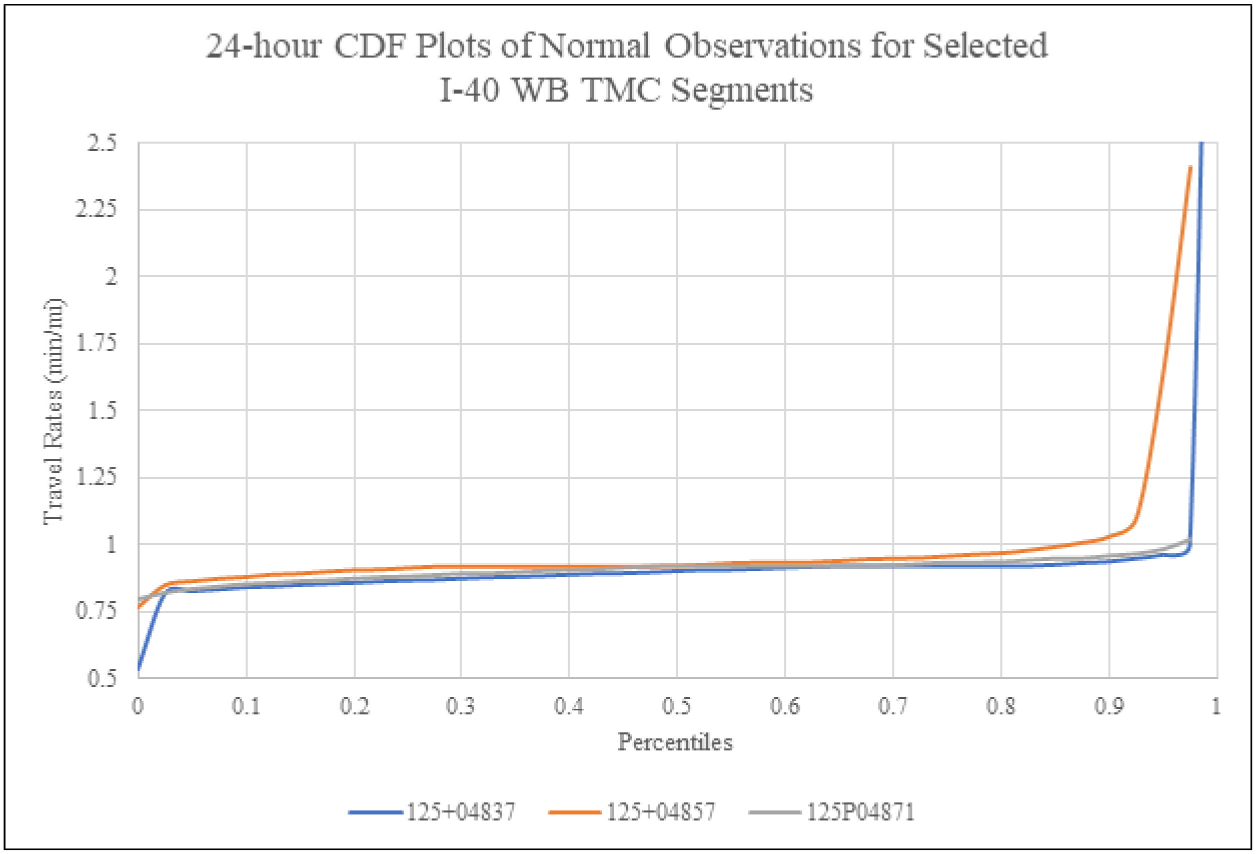
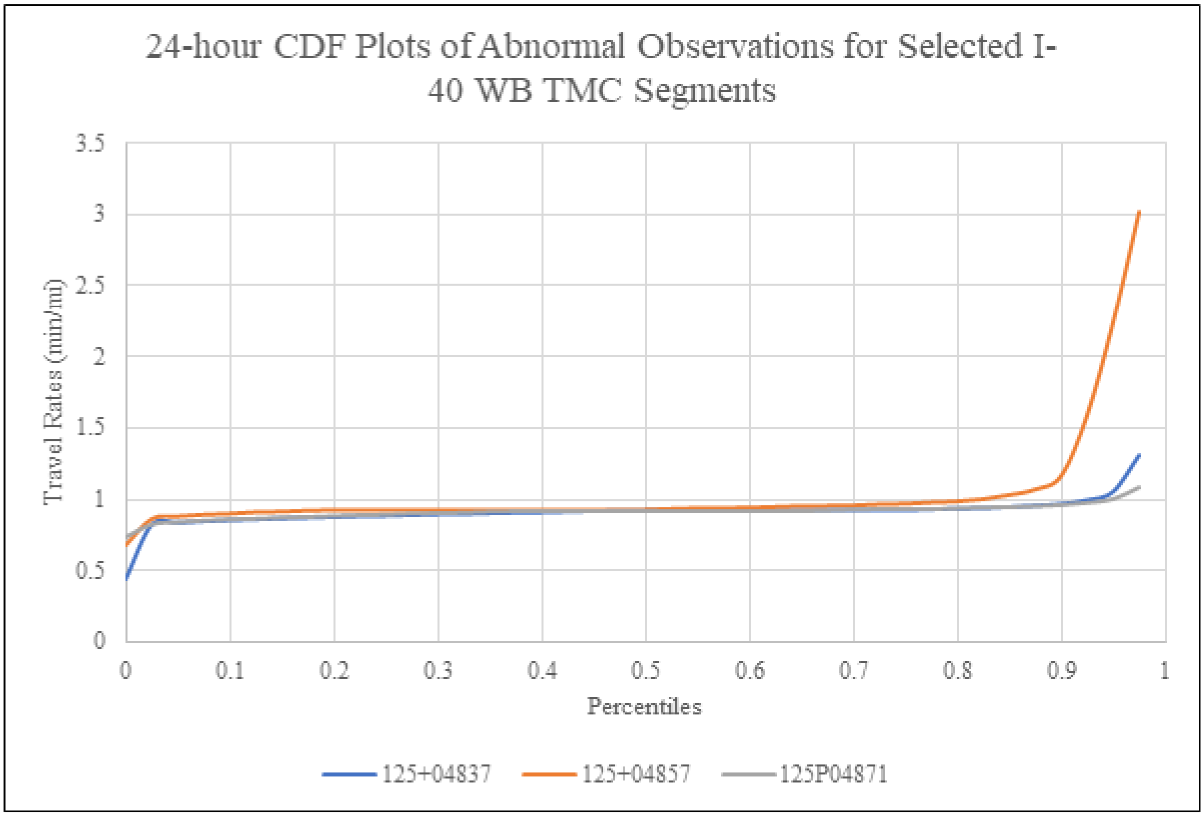


Exhibit I-B - 6: CDF plots of abnormal travel rates for selected I-40 WB TMC segments for all temporal intervals.



Based on the previously noted speed distribution data for I-40 WB, variability was greater during the AM peak period. Therefore, this temporal analysis period was selected for additional summary. Table I-B - 11 indicates major percentile values and the tabulated buffer time index for the AM peak period.

Exhibit I-B - 7 displays CDF plots for normal observations during the AM peak period. Exhibit I-B - 8 shows the CDF plots for abnormal observations during the AM peak period. For normal observations 125+04837, 125+04857, and 125P04871 reported the 17^{th}, 4^{th}, and 37^{th} highest buffer time index during the AM peak period. 125P04856, located upstream of 125+04857, had the highest buffer time index during the analysis period. Among abnormal conditions the TMC segments experienced the 12^{th}, 3^{rd}, and 43^{rd} highest buffer time indices out of 51 TMC segments along I-40 WB.

Table I-B - 11: Key percentiles for abnormal travel rate observations of selected I-40 WB TMC segments during the AM peak period

	125+04837	125+04857	125P04871
Normal Observation AM Peak Percentiles			
0.05	0.8324	0.8781	0.8310
0.25	0.86419	0.9293	0.8722
0.5	0.8908	0.9815	0.9065
0.75	0.9231	1.9433	0.9375
0.95	1.0219	3.1587	0.9770
Buffer Time Index	0.1551	2.2184	0.0778
Mean Travel Rate	0.9179	1.0947	1.0889
Standard Deviation	0.2791	0.3301	0.6032
Abnormal Observation AM Peak Percentiles			
0.05	0.8346	0.8682	0.8333
0.25	0.8734	0.9189	0.8824
0.5	0.9038	0.9522	0.9123
0.75	0.9375	1.1970	0.9375
0.95	1.5100	3.5729	1.0120
Buffer Time Index	0.6702	2.7521	0.1093

Exhibit I-B - 7: CDF plots of normal travel rates for selected I-40 WB TMC segments during the AM peak period

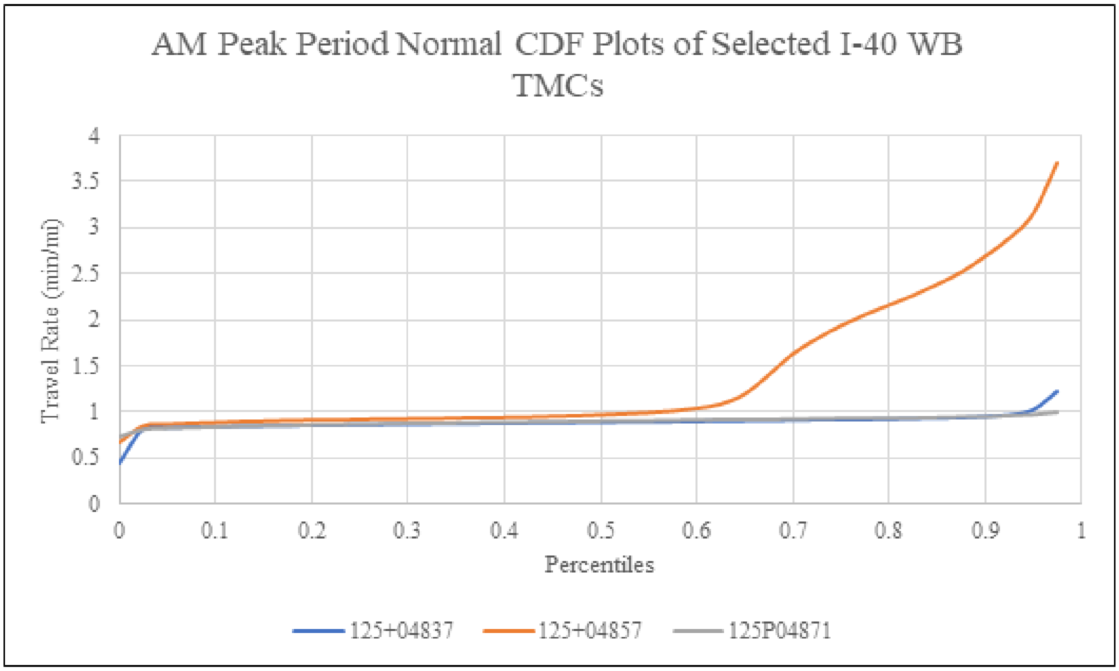
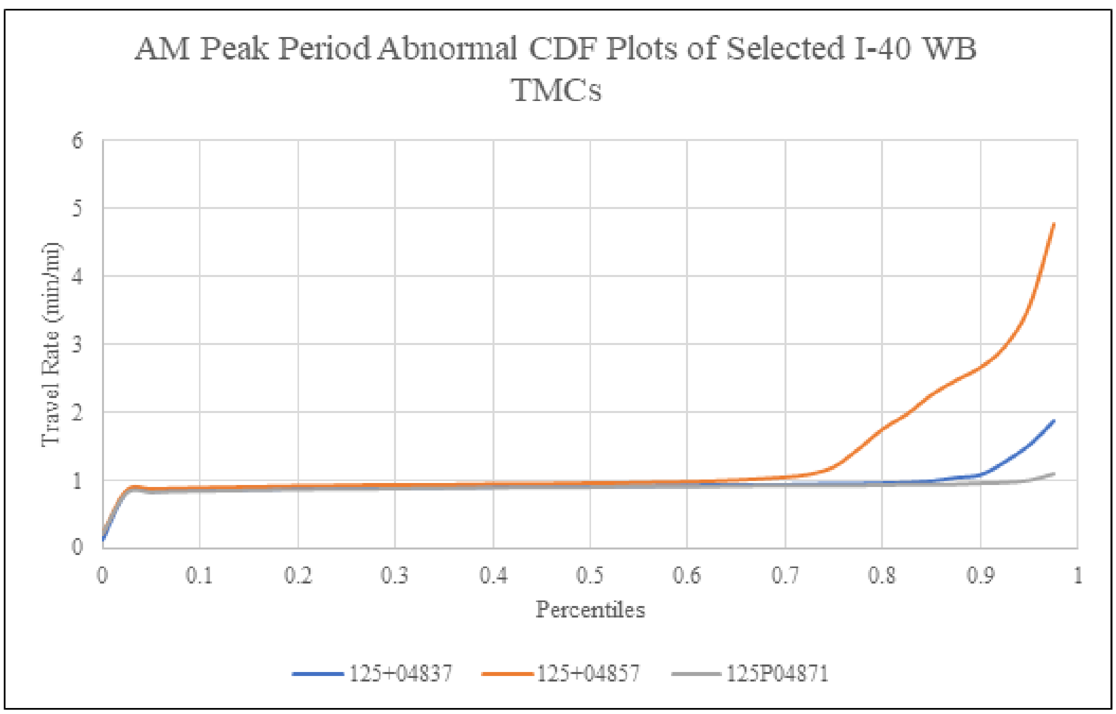


Exhibit I-B - 8: CDF plots of abnormal travel rates for the selected I-40 WB TMC segments during AM peak period



During the AM peak period, 125+04857 exhibits the most travel rate variation, especially in the uppermost quartile. Measurable variability was observed along 125+04837 above the 90^{th} percentile, while 125P04871 did not show material variation up to the 97.5^{th} percentile. Between the 60^{th} and 70^{th} percentiles, more variation was observed for 125+04857 during the normal operating conditions than abnormal. This could be caused by differences in the sample size of the normal and abnormal time/space observation set. Additionally, the CDF plots suggest segment 125+04857 experiences significant levels of recurring congestion not accounted for by external events.

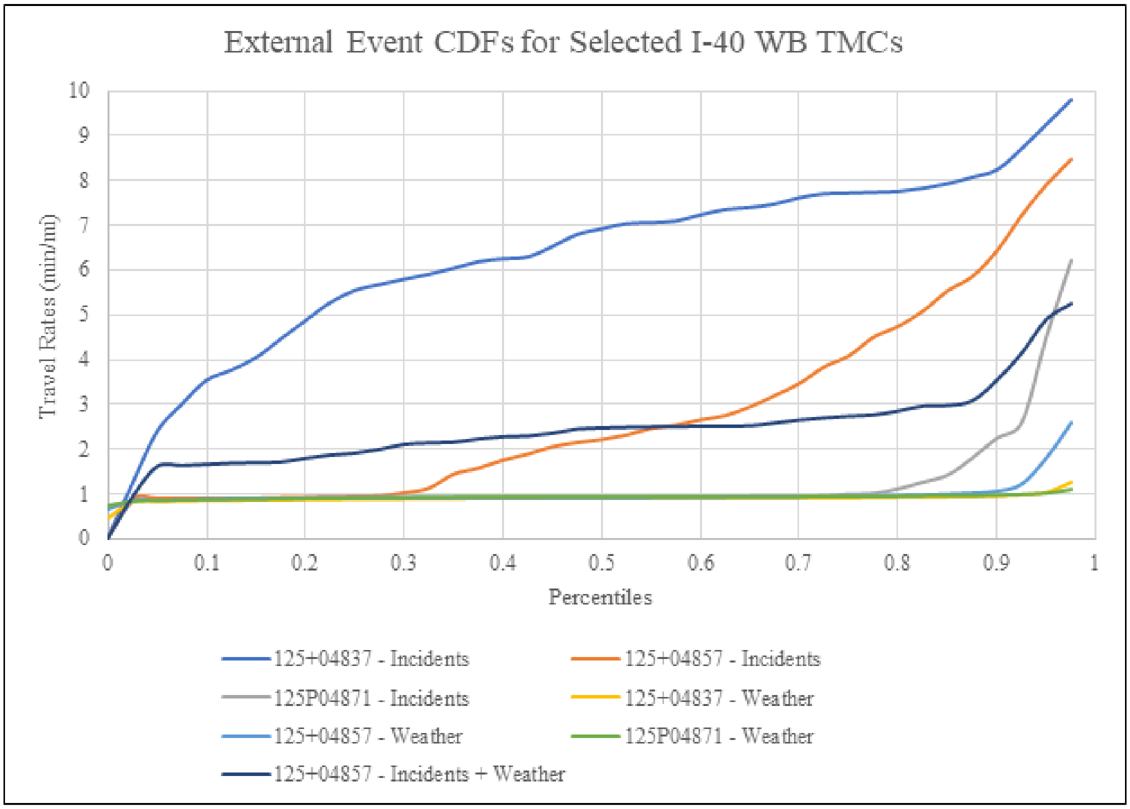
CDF distributions were also generated for external event combinations for all temporal intervals. Distributions were generated for time/space observations with incidents only, weather flags only, and both an incident and weather flag. Table I-B - 12 shows critical percentiles and other metrics for all three external event distributions. Valid data was not available for the incident and weather external event scenario for 125+04837 and 125P04871, therefore, buffer time indices were not tabulated for those TMC segments. Buffer time indices generated for the incident only dataset had significantly higher travel rates than the other external event distributions.

125+04837 experienced higher travel rates than 125 + 04857 across all major percentiles, which suggests a major incident significantly impacted 125+04837. Due to the inflated travel rates across the distribution, 125+04837 had the lowest buffer time index of the three TMC segments. 125P04871 had the highest buffer time index among all three selected TMCs. 125+04837, 125+04857, and 125P04871 reported the 41^{st}, 22^{nd}, and 12^{th} highest buffer time indices for incident only observations and had the 24^{th}, 3^{rd}, and 44^{th} highest buffer time indices for the weather only observations. For the incident only distribution, 125P04872 experienced the highest buffer time index, 10.1736. For the weather only distribution, 125P04856 reported the highest buffer time index, 1.1272. Due to lack of valid data for many TMC segments during incident and weather condition, buffer time index rankings were not tabulated. Exhibit I-B - 9 shows the CDF plots for each external event and selected I-40 WB TMC segment.

Table I-B - 12: Key percentile values and buffer time index tabulations for incident only, weather only, and weather plus incident observations over selected I-40 WB TMC segments.

	125+04837	125+04857	125P04871
Incidents Only			
0.05	2.3874	0.9227	0.8573
0.25	5.5407	0.9559	0.9218
0.5	6.9177	2.2270	0.9375
0.75	7.7148	4.0935	1.0003
0.95	9.2573	7.9101	4.5116
Buffer Time Index	0.3382	2.5519	3.8123
Weather Only			
0.05	0.8368	0.8771	0.8476
0.25	0.8851	0.9231	0.9052
0.5	0.9231	0.9237	0.9231
0.75	0.9240	0.9671	0.9375
0.95	1.0482	1.8124	1.0087
Buffer Time Index	0.1355	0.9622	0.0928
Incident and Weather			
0.05	N/A	1.6106	N/A
0.25	N/A	1.9117	N/A
0.5	N/A	2.4792	N/A
0.75	N/A	2.7428	N/A
0.95	N/A	4.9179	N/A
Buffer Time Index	N/A	0.9837	N/A

Exhibit I-B - 9: CDF plots of external event operating conditions during all time intervals for selected I-40 WB TMC segments



I-440 Eastbound Facility Analysis

Three TMC segments were selected from 30 TMCs along I-440 EB. The entire facility is located within the study area therefore the three TMC segments are spatially distributed along the entire directional facility. 125-04983 is a two-lane directional segment located near the partial interchange with Melbourne Rd. at Exit 1 near the western terminus of I-440 at I-40/US 1/US 64. 125-04991, a three-lane directional facility, is located near the I-440 and US 70 / Glenwood Avenue interchange at Exit 7. The easternmost TMC selected is 125-04904, a four-lane directional segment located near the Poole Rd. interchange at Exit 15. US 64 and I-87 are concurrent with I-440 along this segment. Table I-B - 13 contains summary data and details for the selected TMC segments.

Table I-B - 14 shows statistical information on the frequency of external events occurring within the selected TMCs.

Table I-B - 13: Descriptions of selected TMC segments along I-440 EB

	125-04983	125-04991	125-04904
Number of Lanes	2	3	4
Length (mi)	0.6243	0.0541	0.2073
Nearest Interchange	Melbourne Rd.	Glenwood Ave.	Poole Rd.
County	Wake	Wake	Wake
Number of Invalid Time/Space Travel Rates	1,682	1,689	1,683
Mean Travel Rate (min/mi)	1.0202	0.9661	0.9509
Buffer Time Index	0.1698	0.1472	0.0890

Table I-B - 14: Breakdown of external event frequencies for selected TMC segments along I-440 EB and each temporal analysis period.

	125-04983	125-04991	125-04904
Temporal intervals with deviant travel rates			
24-hour	2197	2689	1904
AM Peak Period	1342	1359	825
PM Peak Period	727	562	101
Weekends	547	220	405
Temporal intervals with an active unplanned incident			
24-hour	52	18	13
AM Peak Period	0	0	0
PM Peak Period	0	0	0
Weekends	52	18	13
Temporal intervals with an active planned incident			
24-hour	52	0	0
AM Peak Period	0	0	0
PM Peak Period	0	0	0
Weekends	52	0	0
Temporal intervals with an active weather event			
24-hour	12507	12506	11972
AM Peak Period	2644	2644	2576
PM Peak Period	1452	1452	1318
Weekends	3800	3800	3675
Temporal intervals with oversaturated flow rates			
24-hour	17	19	0
AM Peak Period	16	0	0
PM Peak Period	1	19	0
Weekends	0	0	0

Table I-B - 15 contains the speed distributions for each of the TMC segments highlighted along I-440 EB for each temporal analysis interval. Ranges are exclusive of the lower end of the speed ranges. The AM peak period observed the highest variability in vehicle speeds, especially along 125-04983, the most variable of the TMCs highlighted in this analysis. During the PM peak hour, 125-04991 experiences the greatest speed variation. Facility-wide just over 80% of vehicle speed observations were greater than 60 mph. The posted speed limit among 125-04983 is only 55 mph and only 60 mph along 125-04991 and 125-04904. However, the free flow speeds are much higher when observed in the field.

Table I-B - 15: Travel speed distributions for the entire facility and three selected TMC segments over all temporal analysis periods for I-440 EB

	125-04983	125-04991	125-04904	Facility
24-hour (all times)				
60+	69.67%	81.93%	89.04%	80.44%
55 - 60	24.64%	14.27%	9.26%	15.59%
45 - 55	3.36%	2.88%	1.13%	2.89%
40 - 45	0.65%	0.37%	0.17%	0.34%
30 – 40	1.00%	0.39%	0.20%	0.40%
15 - 30	0.55%	0.17%	0.15%	0.27%
0 - 15	0.15%	0.01%	0.04%	0.08%
AM Peak Period				
60+	45.83%	81.14%	93.34%	76.07%
55 - 60	27.59%	14.72%	5.73%	15.77%
45 - 55	13.34%	3.26%	0.84%	5.59%
40 - 45	3.88%	0.36%	0.04%	0.86%
30 – 40	6.38%	0.31%	0.04%	1.05%
15 - 30	2.80%	0.21%	0.01%	0.59%
0 - 15	0.18%	0.00%	0.00%	0.07%
PM Peak Period				
60+	84.54%	78.57%	97.05%	85.68%
55 - 60	5.95%	8.96%	1.32%	5.78%
45 - 55	5.94%	8.95%	1.32%	5.78%
40 - 45	0.92%	1.33%	0.13%	0.70%
30 – 40	1.11%	1.42%	0.09%	0.87%
15 - 30	0.97%	0.74%	0.08%	0.85%
0 - 15	0.57%	0.04%	0.01%	0.34%
Weekday Off Peak				
60+	78.29%	87.33%	89.34%	83.92%
55 - 60	19.37%	10.59%	9.75%	13.81%
45 - 55	1.79%	1.73%	0.75%	1.88%
40 - 45	0.09%	0.15%	0.07%	0.13%
30 – 40	0.13%	0.13%	0.05%	0.13%
15 - 30	0.20%	0.06%	0.02%	0.09%
0 - 15	0.14%	0.00%	0.02%	0.04%
Weekend (Sat. / Sun.)				
60+	70.64%	81.05%	87.12%	80.29%
55 - 60	27.79%	16.22%	9.48%	16.57%
45 - 55	1.13%	1.99%	1.82%	2.25%
40 - 45	0.16%	0.31%	0.42%	0.30%
30 – 40	0.21%	0.38%	0.57%	0.38%
15 - 30	0.07%	0.06%	0.48%	0.19%
0 - 15	0.01%	0.00%	0.12%	0.03%

Table I-B - 16 contains critical percentile values and tabulated buffer time index values for the highlighted TMC segments for normal and abnormal observations from all temporal analysis intervals. Except for 125-04904, higher buffer time indices were observed during normal conditions rather than abnormal. This is likely attributed to higher median travel rates at the 50th percentile. During normal operating conditions, 125-04983, 125-04991, and 125-04904 reported the 6th, 11th, and 29th highest travel time indices. The highest buffer time index occurred at the westernmost TMC segment, 125-04984. This section of I-440 is only two lanes in each direction and forms a bottleneck between US 1/US 64 south of I-40 and downstream segments of I-440 EB that have more than three lanes. This segment is part of a route from office parks in north Raleigh to residential communities in Cary and Apex to the south.

During abnormal operating conditions 125-04983, 125-04991, and 125-04904 reported the 4th, 11th, and 27th highest buffer time indices among 30 TMC segments along I-440 EB. The highest buffer time index was reported by 125N0984, immediately downstream of 125-04984.

Table I-B - 16: Key percentiles and buffer time index of normal and abnormal travel rates for selected I-440 EB TMCs for all temporal intervals

	125-04983	125-04991	125-04904
Normal Observation Percentiles			
0.05	0.9059	0.8792	0.8750
0.25	0.9643	0.9231	0.9288
0.5	0.9677	0.9445	0.9375
0.75	1.0007	0.9836	0.9615
0.95	1.1321	1.0836	1.0209
Buffer Time Index	0.1698	0.1472	0.0890
Mean Travel Rate	1.0175	0.9661	0.9509
Standard Deviation	0.3891	0.1210	0.1184
Abnormal Observation Percentiles			
0.05	0.9132	0.8905	0.8955
0.25	0.9677	0.9231	0.9375
0.5	0.9677	0.9416	0.9524
0.75	1.0031	0.9836	0.9717
0.95	1.1538	1.1088	1.0633
Buffer Time Index	0.1503	0.1273	0.0943

Exhibit I-B - 10 displays CDF plots of 24-hour normal observations for each selected TMC segment. Exhibit I-B - 11 shows CDF plots for abnormal conditions during all temporal analysis periods. These plots indicate little variation between the normal observation distributions and the abnormal observation distributions. 125-04991 and 125-04904 track closely through the 50th percentile, however, 125-04491 starts experiencing greater variation in the upper portion of the distributions. 125-04983 report travel rates higher than the other TMC segments throughout the entire distribution likely due to the two-lane cross-section.

Exhibit I-B - 10: CDF plots of normal travel rates for selected I-440 EB TMC segments for all temporal analysis periods

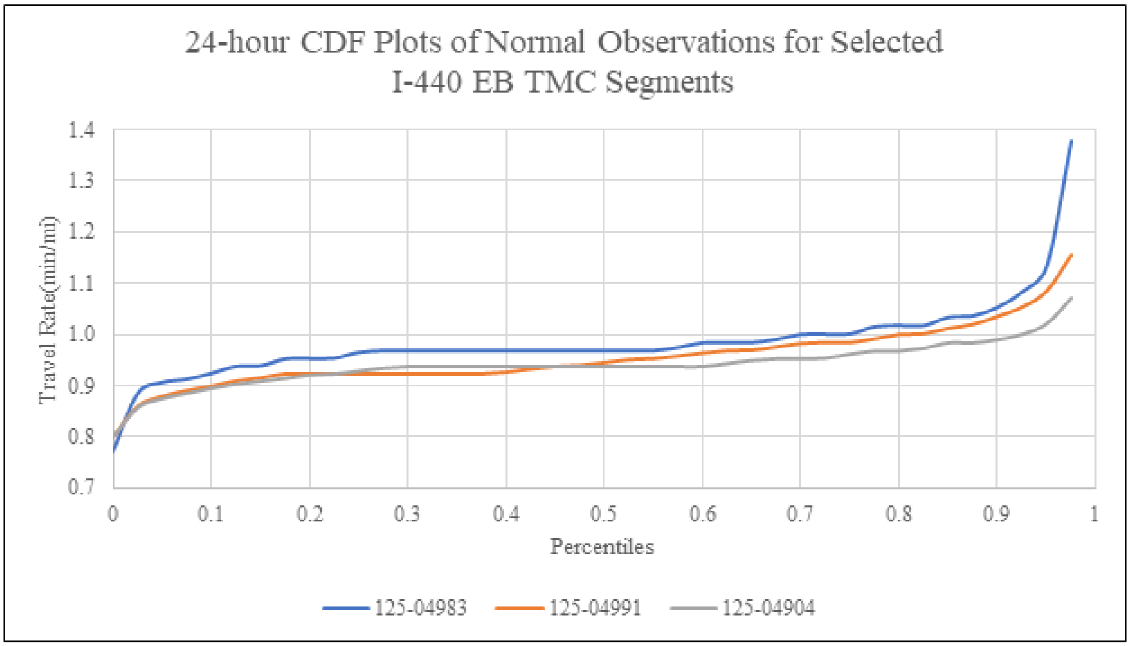
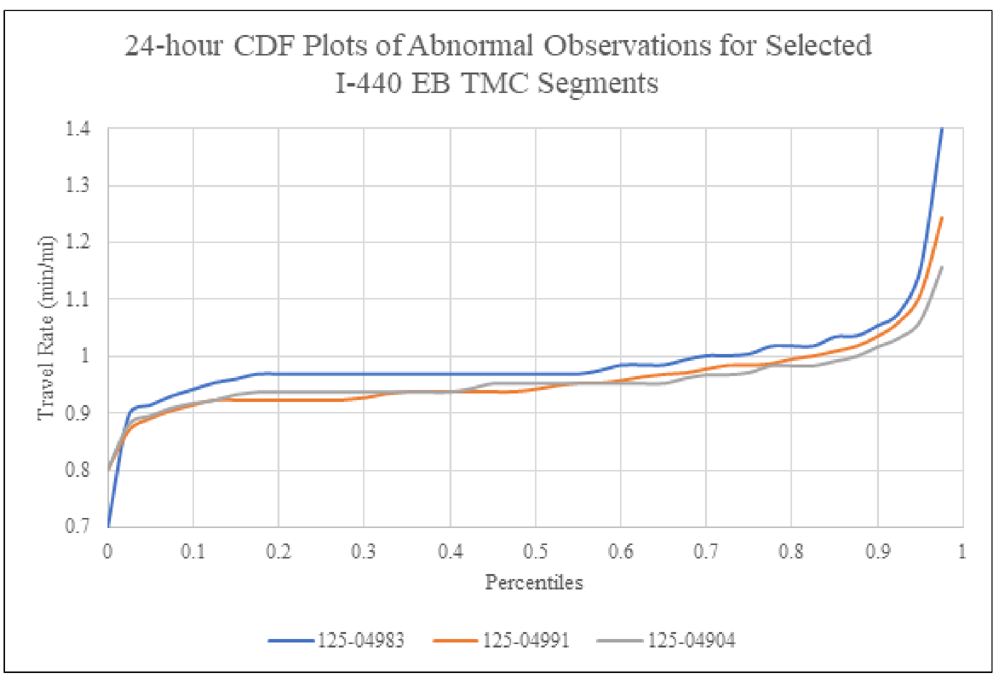


Exhibit I-B - 11: CDF plots of abnormal travel rates for selected I-440 EB TMC segments for all temporal intervals



Previous speed distribution analysis for I-440 EB indicated that travel time/rate variability was higher in the AM peak period. Therefore, this temporal analysis period was further highlighted. Table I-B - 17 shows major percentile values and buffer time indices for normal and abnormal observations during the AM peak period. Exhibit I-B - 12 shows CDF plots for normal observations during the morning peak period and Exhibit I-B - 13 displays the CDF plots for abnormal operating conditions during the AM peak.

Table I-B - 17: Key percentiles for abnormal travel rate observations of selected I-440 EB TMC segments during the AM peak period

	125-04983	125-04991	125-04904
Normal Observation AM Peak Percentiles			
0.05	0.8985	0.8578	0.8800
0.25	0.9677	0.9190	0.9231
0.5	0.9979	0.9524	0.9473
0.75	1.0526	0.9836	0.9677
0.95	1.6501	1.0604	1.0000
Buffer Time Index	0.6535	0.1135	0.0557
Mean Travel Rate	1.0813	0.9609	0.9473
Standard Deviation	0.3094	0.1007	0.0649
Abnormal Observation AM Peak Percentiles			
0.05	0.8985	0.8660	0.8955
0.25	0.9677	0.9238	0.9375
0.5	1.0000	0.9524	0.9524
0.75	1.0345	0.9836	0.9836
0.95	1.6457	1.1269	1.0803
Buffer Time Index	0.6457	0.1823	0.1343

125-04983 reported a slightly lower buffer time index under abnormal conditions, however, the other TMCs experienced higher buffer time indices when conditions were abnormal. 125-04983, 125-04991, and 125-04904 had the 3rd, 12th, and 30th highest buffer time indices during normal operating conditions. 125-04984, the easternmost I-440 EB segment, reported the highest buffer time index, 1.1042. During abnormal conditions, the TMCs had the 3rd, 13th, and 23rd highest buffer time indices. 125N04984 reported the highest buffer time index during abnormal conditions, 0.8019. During abnormal conditions higher rates observed at lower percentiles, thus decreasing the buffer time index. The CDF plots show that 125-04983 had higher variation during normal operations while the others were worse during abnormal conditions. Due to high levels of recurring congestion along 125-04983, adverse impacts due to external events may be masked by the lack of capacity.

Exhibit I-B - 12: CDF plots of normal rates for selected I-440 EB TMC segments during the AM peak period

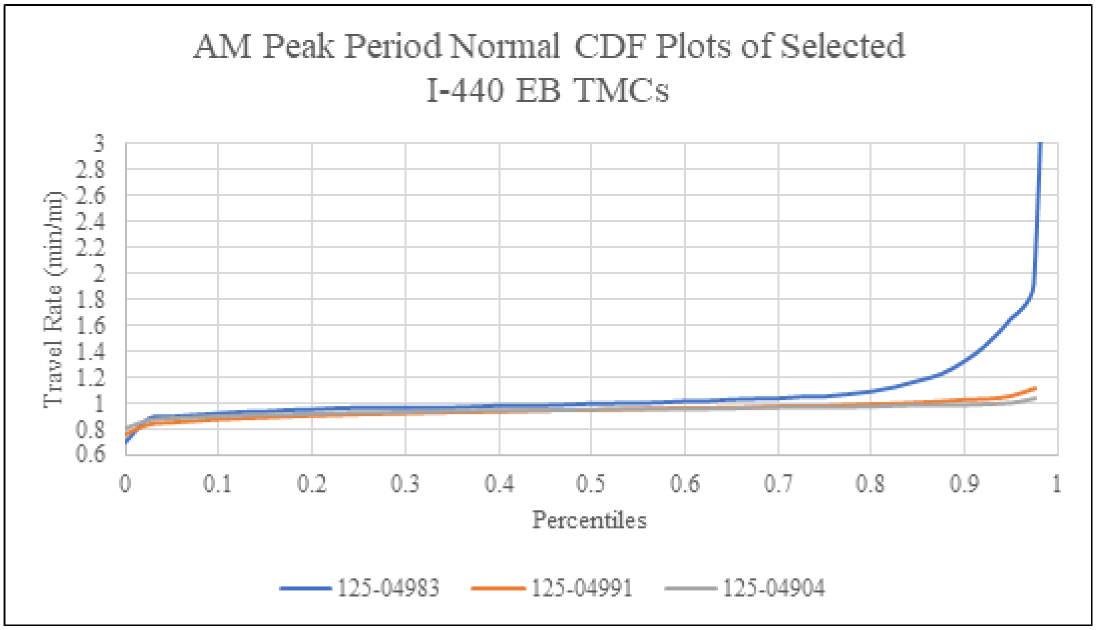
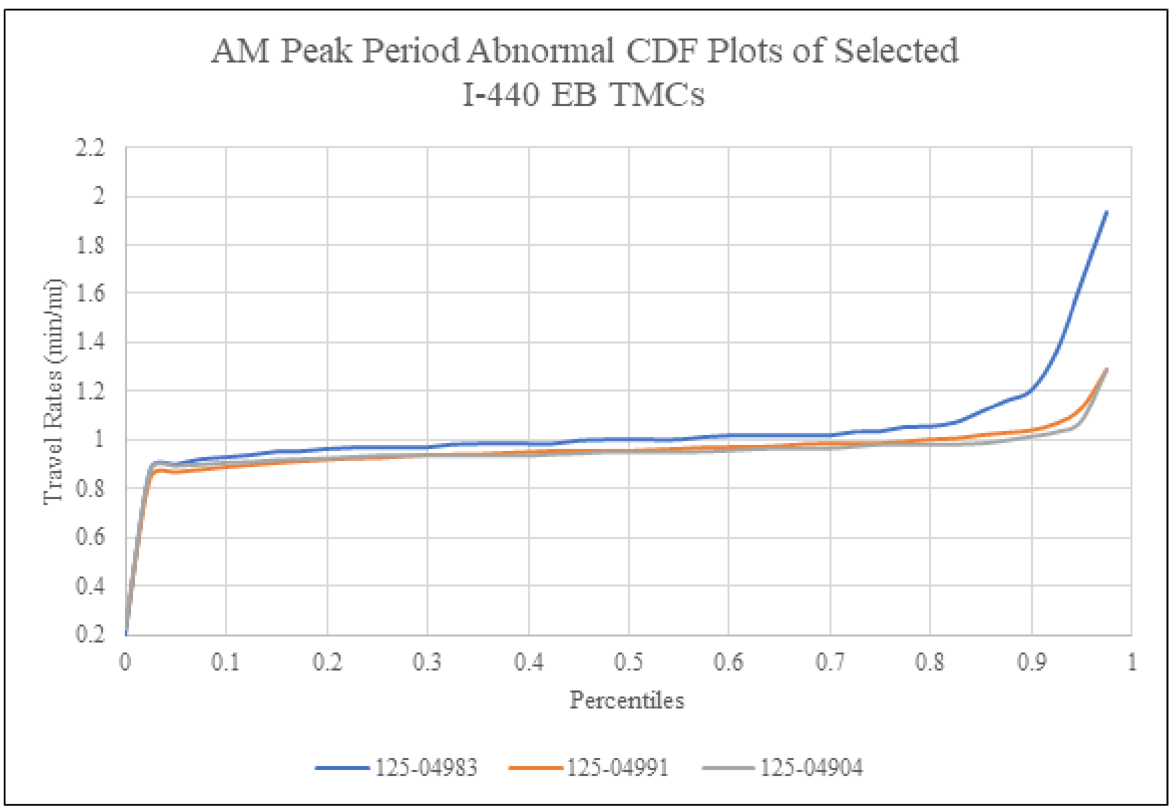


Exhibit I-B - 13: CDF plots of abnormal travel rates for the selected I-440 EB TMC segments during the AM peak period.



CDF distributions were also generated for external event combinations for all temporal intervals. Distributions were generated for time/space observations with incidents only, weather flags only, and both an incident and weather flag. Table I-B - 18 indicates the critical percentiles and other measures for all three external event combinations. Incident-only observations reported higher absolute travel times. However, the buffer time index was higher for weather-only observations for 125-04983. When weather and incidents were concurrent, absolute travel rates increased but variability across the distribution of observed travel rates slightly decreased.

125-04983, 125-04991, and 125-04904 had the 28^{th}, 15^{th}, and 17^{th} highest buffer time index respectively for incident only observations. 125N04988, located near the US 1 Capital Blvd. interchange, reported the highest buffer time index for incident only observations, 4.3220. These TMCs had the 8^{th}, 12^{th}, and 27^{th} highest buffer time index for weather only observations. 125-04989 reported the highest buffer time index, 3.8029, near the Wake Forest Rd. interchange for weather only observations. For combined weather and incident observations, the TMCs experienced the 28^{th}, 13^{th}, and 15^{th} highest buffer time index. The highest buffer time index for this category of all 30 TMCs was 4.7018 and was reported for 125N04980, a segment located at the Wade Avenue interchange.

Exhibit I-B - 14 shows the CDF plots for incident only observations, Exhibit I-B - 15 shows the CDF plots for weather only observations, and Exhibit I-B - 16 shows the CDF plots for the incident and weather observations.

Table I-B - 18: Key percentile value and buffer time index tabulations for incident only, weather only, weather plus incident observations over selected I-440 EB TMC segments

	125-04983	125-04991	125-04904
Incidents Only			
0.05	1.5467	1.5419	0.9524
0.25	1.8399	2.1246	1.7236
0.5	1.9969	2.5968	3.0821
0.75	2.3336	3.6308	4.2181
0.95	3.7849	6.9285	7.7569
Buffer Time Index	0.8954	1.6681	1.5167
Weather Only			
0.05	0.9196	0.8917	0.8955
0.25	0.9677	0.9231	0.9375
0.5	0.9677	0.9459	0.9524
0.75	1.0169	0.9864	0.9775
0.95	1.9113	1.3501	1.1070
Buffer Time Index	0.9750	0.4273	0.1624
Incident and Weather			
0.05	1.6384	1.5949	1.2919
0.25	1.8462	2.1643	1.9017
0.5	1.9971	2.6694	3.1964
0.75	2.3016	3.7460	4.4891
0.95	3.5966	6.9684	7.8822
Buffer Time Index	0.8009	1.6105	1.4659

Exhibit I-B - 14: CDF plots of incident only observations during all temporal intervals for selected I-440 EB TMC segments

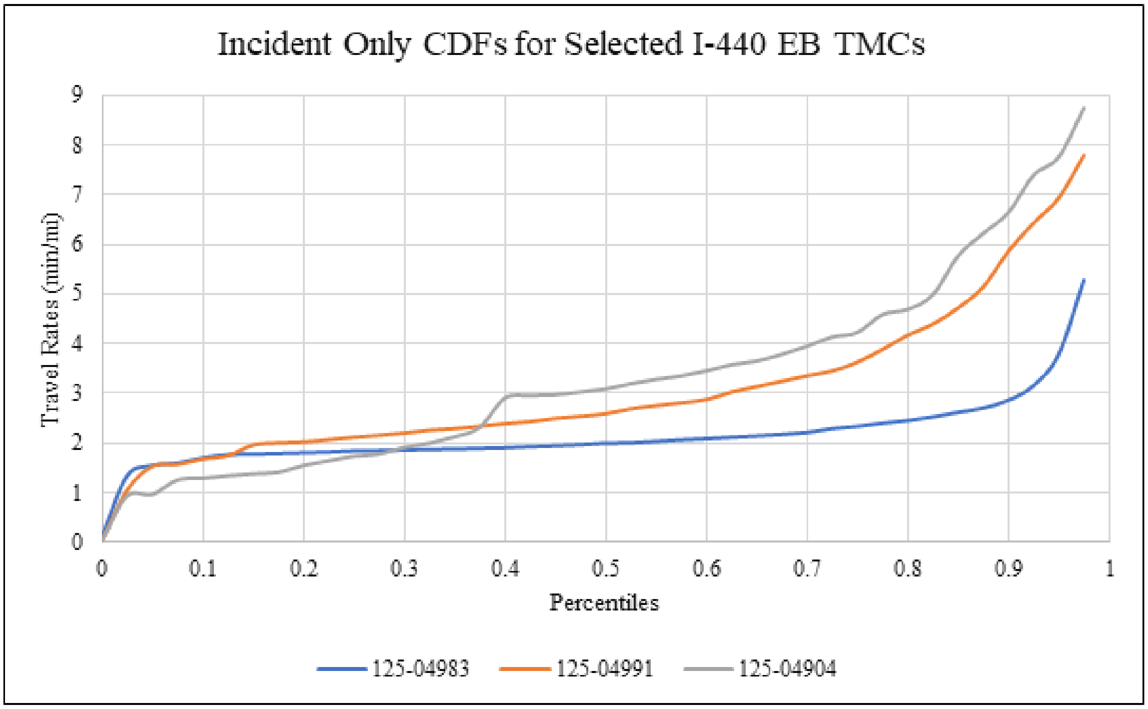


Exhibit I-B - 15: CDF plots of weather only observations during all temporal intervals for selected I-440 EB TMC segments

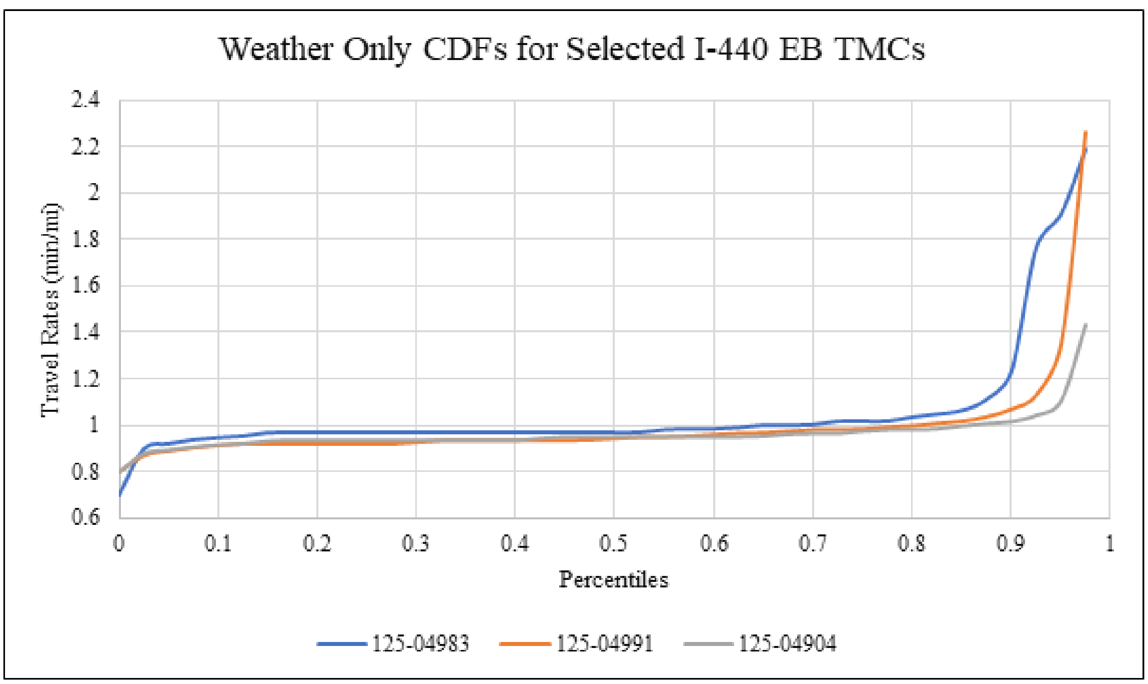
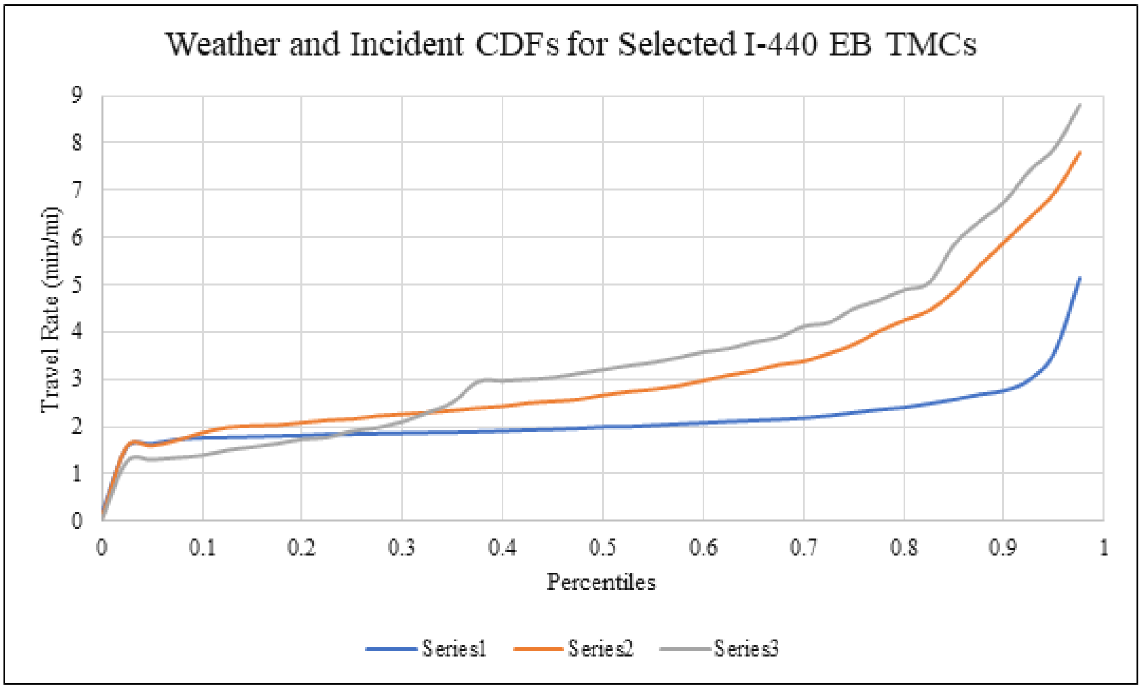


Exhibit I-B - 16: CDF plots of weather and incident observations during all temporal intervals for selected I-440 EB TMC segments



I-440 Westbound

Three TMC segments along I-440 WB were highlighted in this subsection. The entire facility was located within the study area. Therefore, the selected segments were distributed along the entire length of the facility. 125P04904 is a four-lane segment near the Poole Rd. interchange at Exit 15 near the southeastern terminus of I-440. 125P04990, a three-lane segment, is located near Exit 8 at the Six Forks Rd. interchange. 125+04984 is a two-lane segment located adjacent to the Jones Franklin Rd. interchange at Exit 1. Table I-B - 19 lists summary data and characteristics for the highlighted TMC segments. Table I-B - 20 shows the frequency of external events along the TMCs for each temporal analysis interval.

Table I-B - 19: Description of selected TMC segments along I-440 WB

	125P04904	125P04990	125+04984
Number of Lanes	4	3	2
Length (mi)	0.6070	0.4620	0.6389
Nearest Interchange	Poole Rd.	Six Forks Rd.	Jones Franklin Rd.
County	Wake	Wake	Wake
Number of Invalid Time/Space Travel Rates	1,682	1,684	1,688
Mean Travel Rate (min/mi)	0.9343	0.9833	0.9882
Buffer Time Index	0.1000	0.1040	0.1320

Table I-B - 20: Breakdown of external event frequencies for selected TMCs along I-440 WB and each temporal analysis period.

	125P04904	125P04990	125+04984
Temporal intervals with deviant travel rates			
24-hour	1628	559	739
AM Peak Period	111	162	608
PM Peak Period	125	168	273
Weekends	319	196	138
Temporal intervals with an active unplanned incident			
24-hour	152	158	18
AM Peak Period	0	0	0
PM Peak Period	0	0	0
Weekends	152	158	18
Temporal intervals with an active planned incident			
24-hour	58	964	77
AM Peak Period	0	0	0
PM Peak Period	0	0	0
Weekends	58	964	77
Temporal intervals with an active weather event			
24-hour	11975	12506	12507
AM Peak Period	2576	2644	2644
PM Peak Period	1318	1452	1452
Weekends	3675	3800	3800
Temporal intervals with oversaturated flow rates			
24-hour	0	546	290
AM Peak Period	0	545	0
PM Peak Period	0	1	290
Weekends	0	0	0

Table I-B - 21 shows the speed distributions for the highlighted TMC segments along I-440 WB over each temporal analysis period. The PM peak period had the highest variability in travel speeds across the entire I-440 WB facility. 125P04904 proves an exception to this trend because the temporal analysis period with the lowest proportion of observed vehicle speeds under 60 mph was the weekend analysis period. Among the highlighted TMCs, 125+04984 only had 44% of speeds above 60 mph, the lowest proportion for any TMC and temporal analysis period. As was the case with I-440 EB, the posted speed limit never exceeds 60 mph, however the free-flow speeds observed by vehicles along the facility are significantly higher.

Table I-B - 21: Travel speed distributions for the entire facility and three selected TMC segments over all temporal analysis periods for I-440 WB

	125P04904	125P04990	125+04984	Facility
24-hour (all times)				
60+	92.11%	83.28%	71.21%	69.22%
55 - 60	6.10%	12.62%	24.85%	24.40%
45 - 55	1.10%	2.07%	3.24%	4.32%
40 - 45	0.15%	0.40%	0.30%	0.51%
30 – 40	0.20%	0.67%	0.26%	0.68%
15 - 30	0.24%	0.68%	0.12%	0.67%
0 - 15	0.10%	0.29%	0.03%	0.20%
AM Peak Period				
60+	94.12%	70.85%	76.12%	64.95%
55 - 60	4.09%	16.35%	21.63%	24.04%
45 - 55	1.00%	5.47%	2.11%	6.99%
40 - 45	0.07%	1.36%	0.12%	1.05%
30 – 40	0.22%	2.49%	0.02%	1.45%
15 - 30	0.22%	2.71%	0.00%	1.16%
0 - 15	0.28%	0.76%	0.00%	0.36%
PM Peak Period				
60+	93.89%	76.72%	44.06%	58.40%
55 - 60	5.40%	13.45%	38.85%	23.70%
45 - 55	0.61%	3.86%	13.82%	9.84%
40 - 45	0.04%	0.95%	1.34%	1.70%
30 – 40	0.05%	1.66%	1.24%	2.50%
15 - 30	0.01%	2.13%	0.57%	2.97%
0 - 15	0.00%	1.24%	0.12%	0.89%
Weekday Off Peak				
60+	91.82%	87.91%	79.84%	72.44%
55 - 60	7.10%	11.23%	18.38%	24.36%
45 - 55	0.96%	0.71%	1.49%	2.88%
40 - 45	0.03%	0.04%	0.14%	0.14%
30 – 40	0.03%	0.04%	0.09%	0.08%
15 - 30	0.05%	0.03%	0.04%	0.07%
0 - 15	0.00%	0.03%	0.02%	0.03%
Weekend (Sat. / Sun.)				
60+	90.78%	84.63%	69.77%	71.64%
55 - 60	5.71%	12.82%	29.08%	24.98%
45 - 55	1.64%	1.83%	0.91%	2.56%
40 - 45	0.42%	0.27%	0.08%	0.25%
30 – 40	0.54%	0.36%	0.10%	0.35%
15 - 30	0.69%	0.09%	0.05%	0.20%
0 - 15	0.22%	0.00%	0.02%	0.04%

Table I-B - 22 shows the critical percentile values and tabulated buffer time index values for the selected TMC segments. Separate metrics were calculated for normal and abnormal observations across all temporal analysis intervals. For each TMC, buffer time indices were higher for abnormal conditions than for normal conditions. During normal operating conditions, 125P04904, 125P04990, and 125+04984 had the 21st, 29th, and 25th highest buffer time indices of the I-440 WB TMC segments. The highest buffer time index, 1.3988, was recorded for 125+04980, a segment located near the Wade Avenue interchange. However, this ranking doesn't account for differences in lane cross-sections. These TMC segments reported the 24th, 17th, and 21st highest buffer time indices for abnormal conditions. 125P04980 had the highest buffer time index among the I-440 WB during abnormal conditions, 0.3940. The TMC segments reporting the most variability in the upper portion of the distribution are located upstream of a bottleneck created at the Wade Avenue interchange, when I-440 WB drops from three lanes to two for the rest of the facility.

Table I-B - 22: Key percentiles and buffer time index of normal and abnormal travel rates for selected I-440 WB TMCs for all temporal intervals

	125P04904	125P04990	125+04984
Normal Percentiles			
0.05	0.8696	0.8934	0.8965
0.25	0.9171	0.9524	0.9564
0.5	0.9231	0.9677	0.9677
0.75	0.9524	0.9935	1.0000
0.95	1.0154	1.0684	1.0955
Buffer Time Index	0.1000	0.1040	0.1320
Mean Travel Rate	0.9343	0.9833	0.9882
Standard Deviation	0.0731	0.2076	0.1475
Abnormal Percentiles			
0.05	0.8771	0.9070	0.9073
0.25	0.9231	0.9677	0.9677
0.5	0.9231	0.9677	0.9677
0.75	0.9589	1.0000	1.0003
0.95	1.0526	1.1321	1.1055
Buffer Time Index	0.1404	0.1698	0.1423

Exhibit I-B - 17 shows the CDF plots for each selected TMC including normal observations over all temporal intervals. Exhibit I-B - 18 displays CDF plots for abnormal conditions during all temporal intervals for each TMC selected along I-440 WB. These plots also show that there wasn't a major gap between the normal and abnormal distributions for each TMC.

Exhibit I-B - 17: CDF plots of normal travel rates for selected I-440 WB TMC segments for all temporal analysis periods

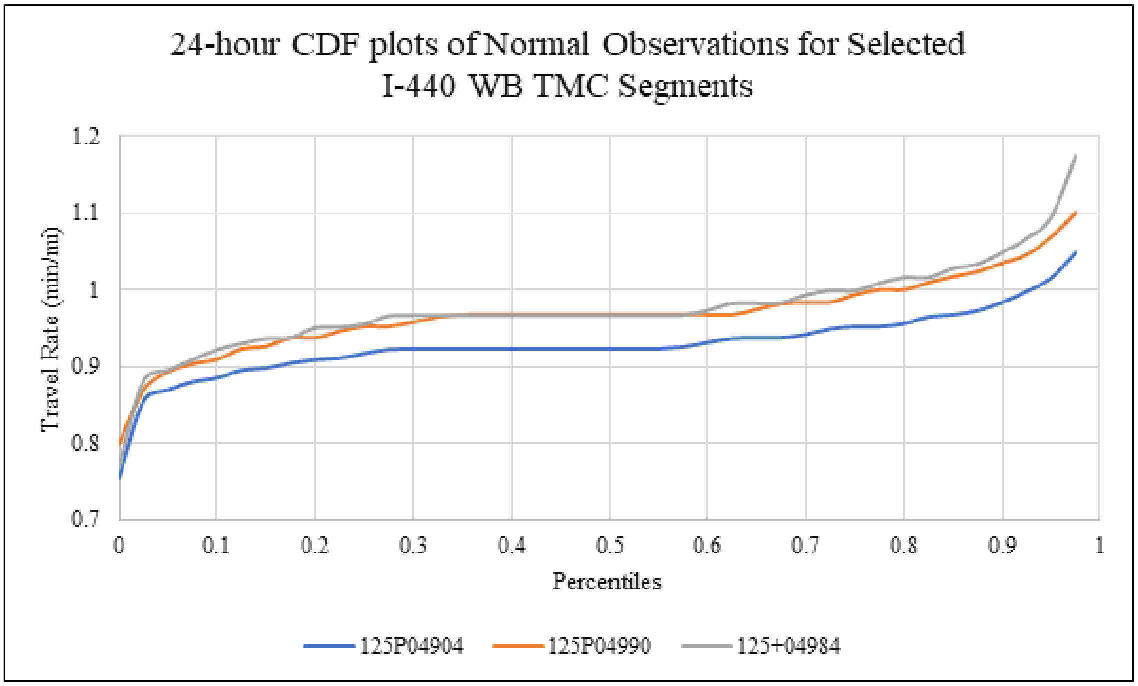
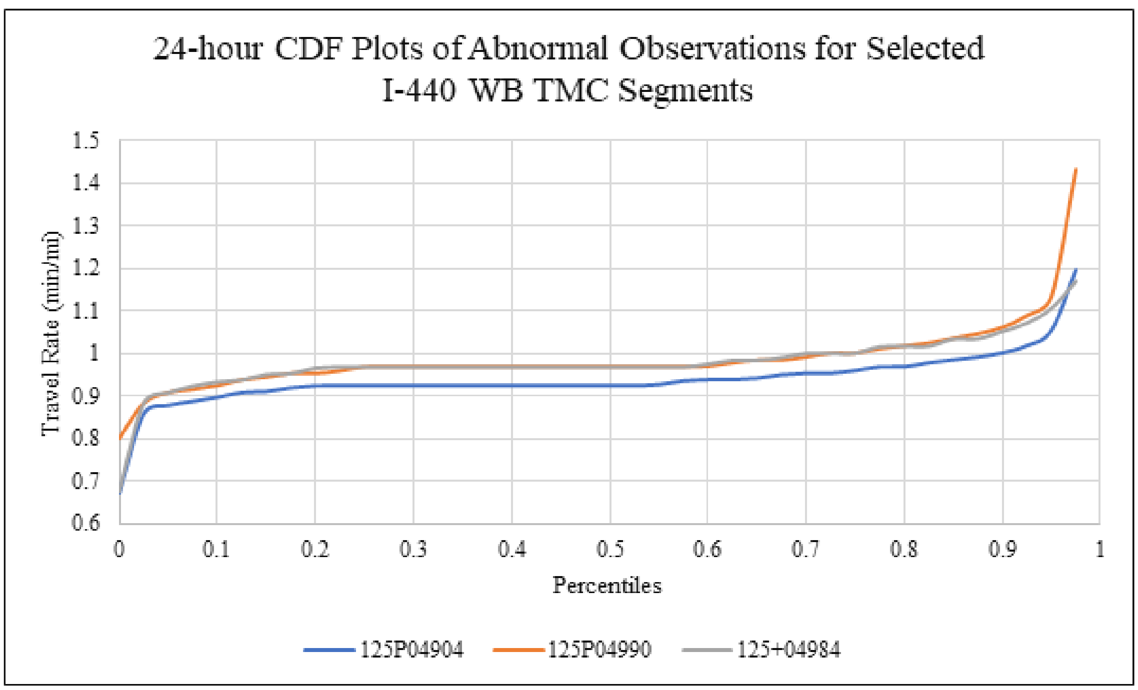


Exhibit I-B - 18: CDF plots of abnormal travel rates for selected I-440 WB TMC segments for all temporal intervals



Based on the speed distribution analysis, the PM peak period had the most travel time variation of all of the temporal analysis periods. Table I-B - 23 shows critical percentiles and buffer time indices for normal and abnormal observations during the PM peak period. 125+04837, 125+04857, and 125P04871 reported the 26th, 19th, and 14th highest buffer time indices for normal operating conditions during the PM peak period. The highest buffer time index reported among all I-440 WB TMCs was 2.6463 along 125P04979, a segment near the Lake Boone Trail interchange. During abnormal conditions, these TMCs had the 24th, 15th, and 18th highest buffer time indices over the PM peak analysis period. 125P04979 also reported the highest buffer time index during abnormal conditions, however, the magnitude of the index was higher at 3.8803.

Table I-B - 23: Key percentiles and buffer time indices for normal travel rates for selected I-440 WB TMCs for all temporal intervals

	125P04904	125P04990	125+04984
Normal Percentiles			
0.05	0.8597	0.8793	0.9091
0.25	0.9047	0.9375	0.9677
0.5	0.9317	0.9693	1.0000
0.75	0.9525	1.0000	1.0359
0.95	1.0121	1.0802	1.1765
Buffer Time Index	0.0862	0.1145	0.1765
Mean Travel Rate	0.9408	0.9890	1.0286
Standard Deviation	0.1721	0.2382	0.2301
Abnormal Percentiles			
0.05	0.8572	0.8879	0.9091
0.25	0.9091	0.952381	0.9703
0.5	0.9375	0.9836	1.0169
0.75	0.9711	1.0299	1.0788
0.95	1.1467	1.4636	1.2976
Buffer Time Index	0.2232	0.4880	0.2760

Exhibit I-B - 19 shows the normal operating condition CDF plots for the selected TMCs along I-440 WB during the PM analysis period. Exhibit I-B - 20 displays the CDF plots for abnormal operating conditions during abnormal conditions for selected I-440 WB TMCs during the PM peak period.

Exhibit I-B - 19: CDF plots of normal observation travel rates for selected I-440 WB TMC segments during the PM peak period

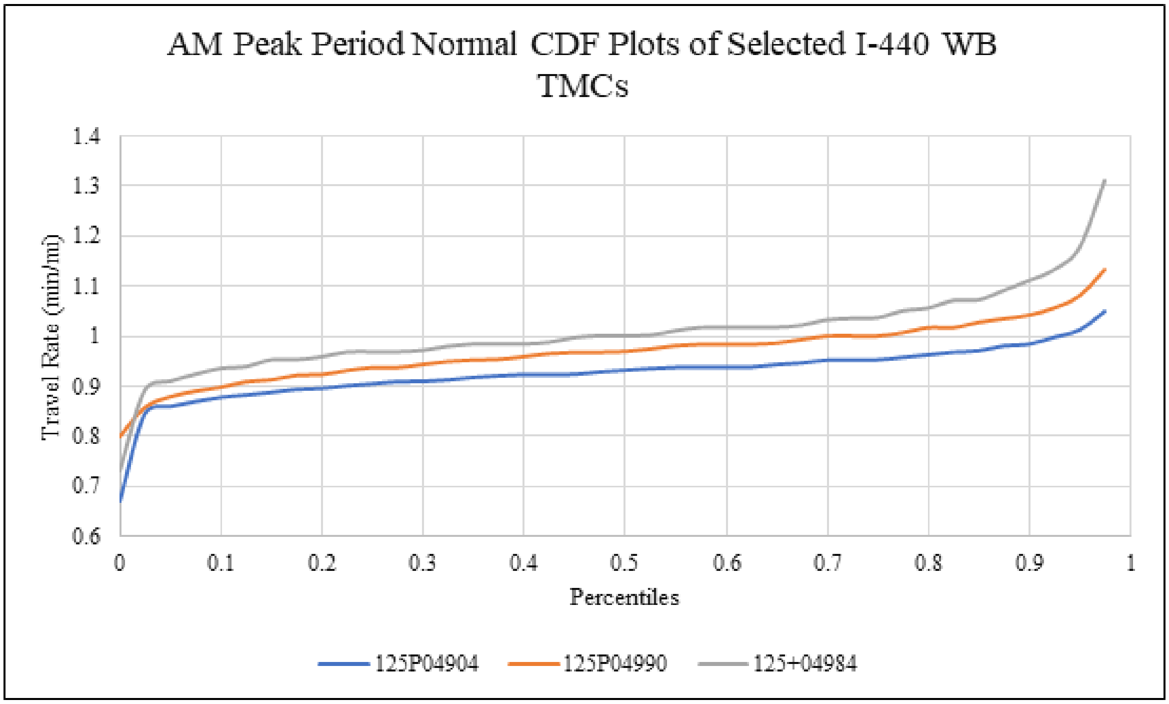
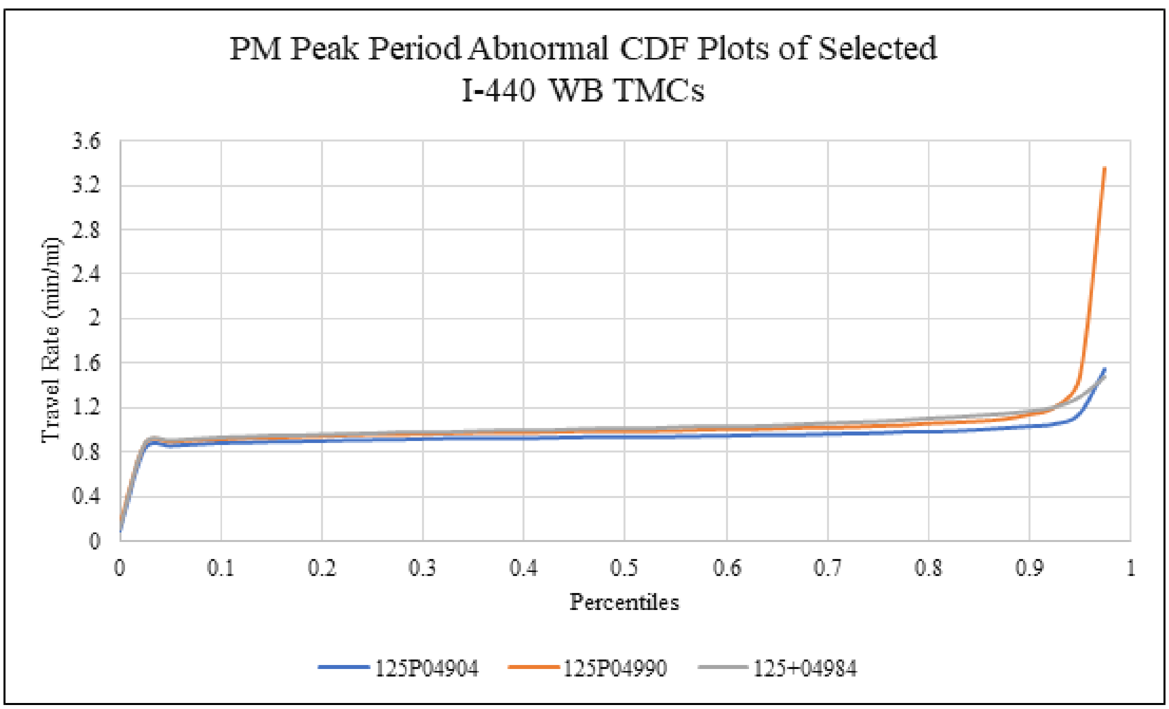


Exhibit I-B - 20: CDF plots of abnormal observation travel rates for selected I-440 WB TMC segments during the PM peak period



During abnormal conditions, the sharpest increase in travel rates was observed for 125P04990. However, during normal conditions, 125+04984 reported the sharpest increase in travel rates. The distributions of each TMC during normal conditions produced CDF curves with similar shapes with stratifying travel rates. The absolute difference in travel rates are likely attributed to changes in the speed limit and number of lanes.

Table I-B - 24 displays critical percentiles and buffer time indices for various combinations of external variables over all temporal intervals. Overall, the magnitude of the travel rates on the upper portion of the cumulative distribution was higher for incident only observations than weather only. However, 125+04984 travel rates did not increase sharply, possibly due to additional lanes limiting the impact of a single lane closure. Concurrent weather and incident events increased travel rates on the lower end of the distribution compared to incident only observations such that the buffer time index decreased relative to incident exclusive events Exhibit I-B - 21 displays CDF plots for incident only observations, Exhibit I-B - 22 displays CDF plots for weather only observations, and Exhibit I-B - 23 shows CDF plots for concurrent weather and incident events.

For incident only observations, 125P04904, 125P04990, and 125+04984 had the 4th, 9th, and 24th highest buffer time indices. The highest buffer time index, 9.3005, was recorded for 125P04988, a segment located near the US 1/US 401/Capital Blvd. interchange. These TMC segments reported the 20th, 18th, and 24th highest buffer time index for weather only observations. For weather only events, the highest buffer time index, 0.2972, occurred along 125P04980, a segment located near the Wade Avenue interchange. Concurrent weather and incident data was not available for 125+04984 as well as several other TMC segments, therefore segment rankings were not tabulated.

Table I-B - 24: Key travel rates (min/mi) by percentile and buffer time indices for incident only, weather only, and weather plus incident observations over select I-440 WB TMC segments

	125P04904	125P04990	125+04984
Incidents Only			
0.05	0.8840	0.8982	0.9329
0.25	0.9231	0.9559	1.0000
0.5	0.9519	0.9836	1.0877
0.75	1.0229	1.0417	1.1622
0.95	3.7311	3.2559	1.2868
Buffer Time Index	2.9197	2.3102	0.1830
Weather Only			
0.05	0.8772	0.9072	0.9063
0.25	0.9231	0.9677	0.9677
0.5	0.9231	0.9677	0.9677
0.75	0.9574	1.0000	1.0000
0.95	1.0485	1.1071	1.0898
Buffer Time Index	0.1359	0.1440	0.1261
Incident and Weather			
0.05	0.6404	0.8950	N/A
0.25	2.7162	0.9524	N/A
0.5	3.4368	0.9677	N/A
0.75	3.9293	1.0151	N/A
0.95	4.7505	1.1277	N/A
Buffer Time Index	0.3823	0.1652	N/A

Exhibit I-B - 21: CDF plots of incident only operating conditions during all time intervals for the selected I-440 WB TMC segments

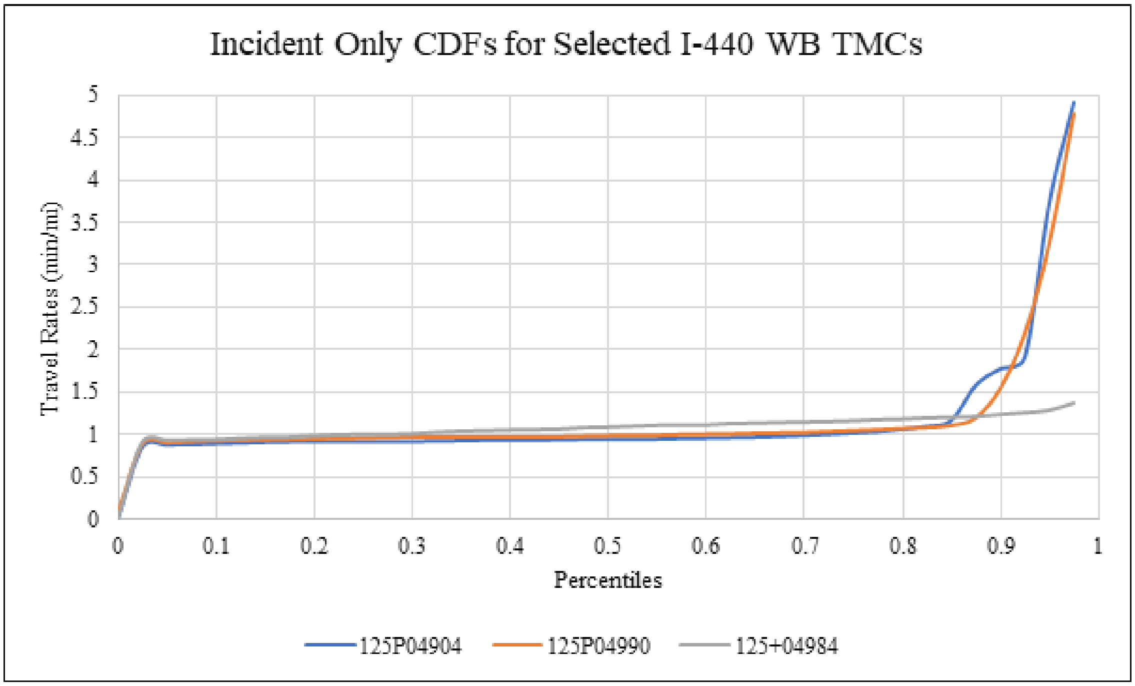


Exhibit I-B - 22: CDF plots of weather only operating conditions during all time intervals for the selected I-440 WB TMC segments

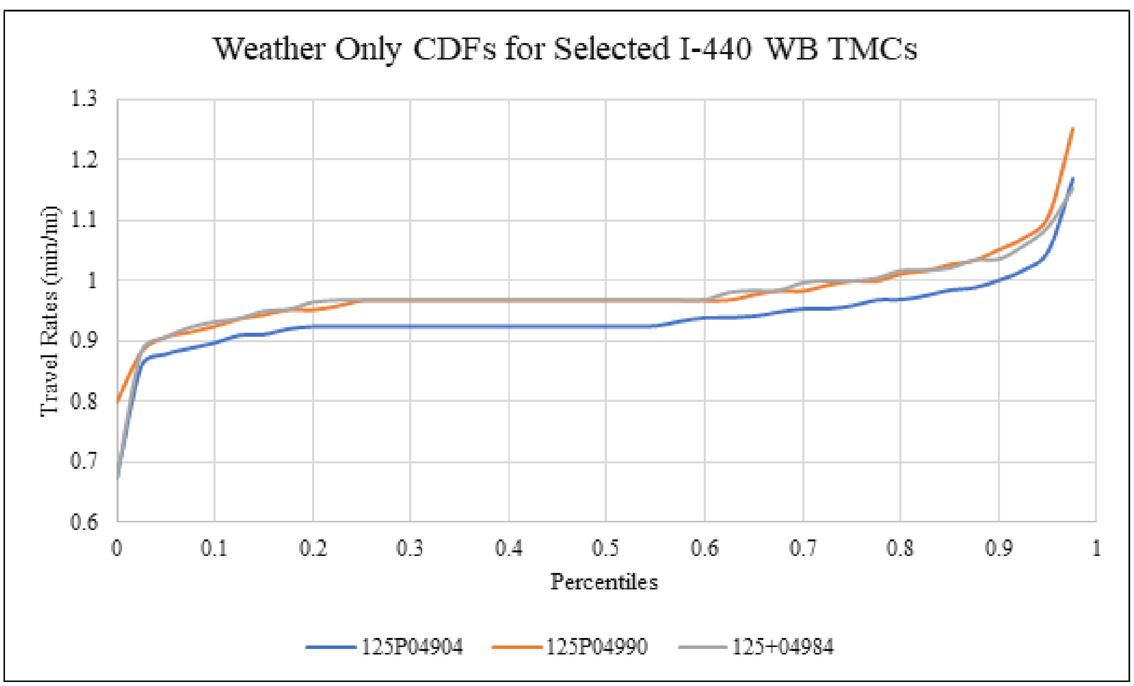
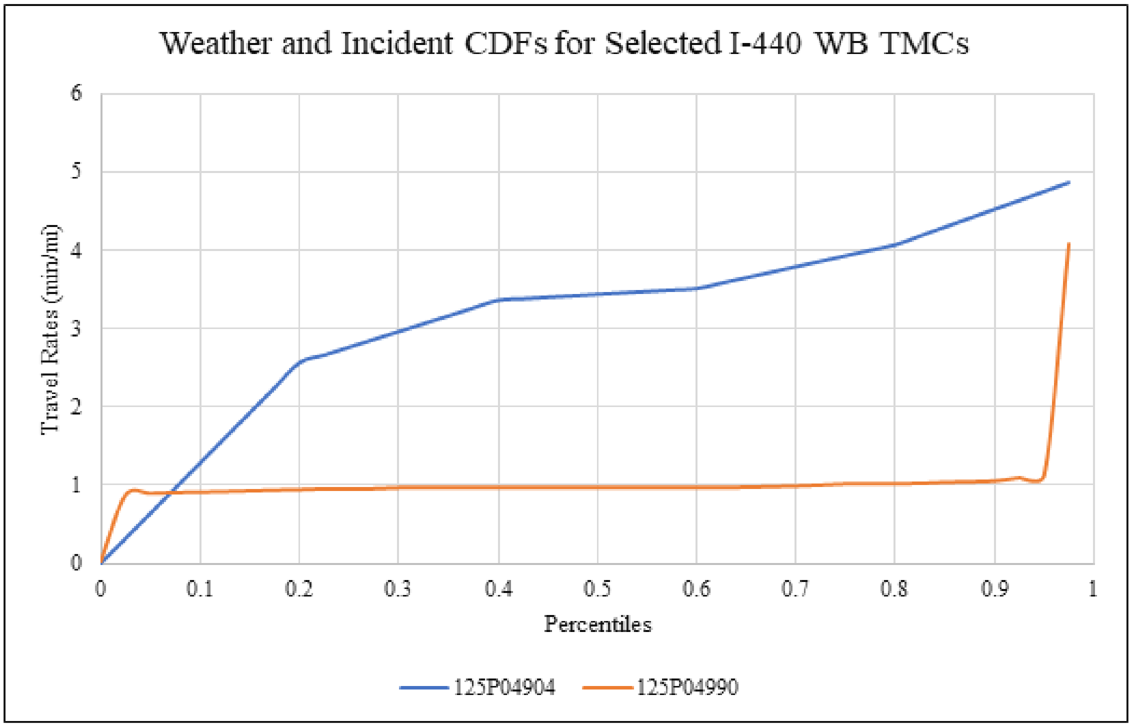


Exhibit I-B - 23: CDF plots of external event operating conditions during all time intervals for selected I-40 WB TMC segments



Route Analyses

Beyond facility-level reliability analysis, popular travel routes were analyzed within the reliability context. The public generally thinks about vehicle trips in terms of their route instead of whole facilities. Therefore, presenting reliability information based on common routes may make reliability information more understandable and relatable to the public. Analysis of routes also facilitates the evaluation of the interrelationship between TMC segments. A subset of incident data was also used to determine the effective incident spatial area of influence beyond the physical boundaries of the site listed in RITIS.

Route 1 WB Analysis – I-540 & US 1 Capital Blvd. to I-40 & Davis Dr.

Table I-B - 25 lists information about the route constructed from a series of TMC segments along I-540 and I-40. Route travel rates were calculated by averaging spatially and temporally accurate synthetic vehicle trajectories across the length of the route. Vehicle trajectories were only included if all the time/space observations used to calculate the continuous trajectory are valid. Reported route travel rates for each temporal interval were classified as abnormal or normal based on the average number of TMC flags each trajectory encountered.

Table I-B - 26 shows the distribution of the average number of flags for each type of external event and possible combinations. The number of time/space observation flags encountered by each synthetic trajectory was averaged to tabulate a value for the temporal interval. Based on the distribution, the normal/abnormal threshold was set at a two-flag average upper bound on normal observations. Using this criterion, speed distributions were generated for normal and abnormal conditions over each temporal analysis period. Table I-B - 27 shows the speed distributions observed along Route 1 WB.

Table I-B - 28 shows statistical measures for Route 1, including mean, standard deviation, key percentiles, and buffer time index for all normal observations, all abnormal observations, normal AM peak period, and PM peak period. Of the external factors, the weather flag was active for the most time intervals. In every instance flow and incident flags were active, the weather flag was active as well. Concurrent and collocated incident and weather events had the highest frequency of observations with the number of flag active TMCs along Route 1 WB

Table I-B - 25: Route 1 WB details and associated TMC descriptions

	I-40 WB	I-540 WB	Entire Route
Number of TMC Segments	7	16	23
Total distance of TMCs (mi)	2.7167	15.9796	18.6963
First TMC Segment	125P04863	125N05083	125N05083
Last TMC Segment	125P04866	125-04896	125P04866

Table I-B - 26: Route 1 WB event flag distributions for incidents, flow rates, and weather over all temporal intervals

Number of Flags	Incidents Only	Weather Only	Flow Only	F & I	I & W	F & W	All
> 0	139	14414	762	137	137	762	137
> 1	110	13780	446	110	110	446	110
> 2	56	13630	204	52	56	204	52
> 3	35	11815	55	25	35	55	25
> 4	23	11716	12	7	23	12	7
> 5	21	11570	3	2	21	3	2
Average	**2.3878**	**13.1549**	**1.5703**				

Table I-B - 27: Route 1 WB speed distribution for both normal and abnormal operating conditions for each temporal analysis period

	24-Hour	AM Peak	PM Peak	Off-Peak	Weekend
Normal					
60+	88.06%	78.80%	89.02%	88.90%	90.09%
55-60	10.35%	11.32%	10.02%	10.73%	9.52%
45-55	0.99%	5.82%	0.66%	0.28%	0.28%
40-55	0.20%	1.13%	0.15%	0.05%	0.07%
30-40	0.23%	1.58%	0.08%	0.04%	0.04%
15-30	0.16%	1.23%	0.07%	0.00%	0.00%
0-15	0.01%	0.11%	0.00%	0.00%	0.00%
Abnormal					
60+	86.78%	78.89%	84.66%	88.48%	88.18%
55-60	10.72%	11.99%	13.97%	11.01%	8.85%
45-55	1.60%	4.92%	0.87%	0.47%	2.07%
40-55	0.37%	1.24%	0.09%	0.02%	0.59%
30-40	0.28%	1.27%	0.09%	0.02%	0.31%
15-30	0.21%	1.39%	0.32%	0.00%	0.00%
0-15	0.04%	0.30%	0.00%	0.00%	0.00%

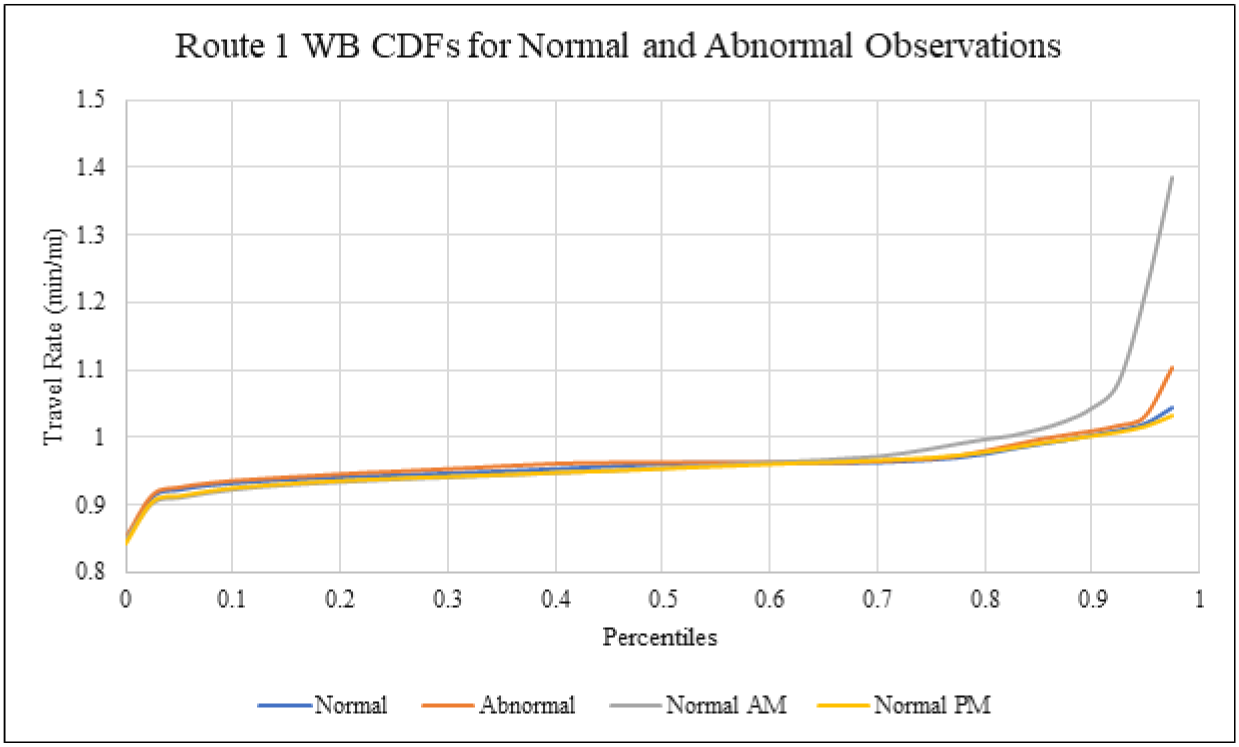
Table I-B - 28: Statistical data and critical percentiles for Route 1 WB

	Normal	Abnormal	Normal AM	Normal PM
Mean Travel Rate	0.9648	0.9775	0.9975	0.9601
Mean S.D.	0.0520	0.1356	0.2257	0.0554
# of Deviant Obs	2134	0	381	190
Percentiles/Travel Rate				
0.05	0.9608	0.9625	0.9535	0.9534
0.25	0.9670	0.9683	0.9821	0.9698
0.5	0.9609	0.9625	0.9535	0.9535
0.75	0.9671	0.9677	0.9829	0.9700
0.95	1.0206	1.0320	1.2120	1.0163
Buffer Time Index	**0.0646**	**0.0681**	**0.2830**	**0.0662**

The largest variation in route travel time was observed in the AM peak period, which is consistent with westbound traffic departing from residential neighborhoods in north Raleigh and traveling to offices near RTP. The PM peak period exhibited the highest difference between normal and abnormal speeds over 60 mph.

Exhibit I-B - 24 displays CDF functions for Route 1 WB travel rates for normal and abnormal observations. The 24-hour distributions closely track each other up to the 95th percentile when the abnormal travel rates exceed normal travel rates. The normal PM peak hour distribution most closely tracked the 24-hour distribution. The normal AM distribution experienced the highest variability at the upper portion of the distribution.

Exhibit I-B - 24: CDF plots of normal and abnormal conditions for Route 1 WB and normal AM and PM peak period distribution plots



Route 1 EB Analysis – I-540 & US 1 to I-40 & Davis Dr. (RTP)

Table I-B - 29 contains information about the route constructed from TMCs along I-540 and I-40. Table I-B- 30 shows the distribution of temporal route observations by the number of TMCs along the route with an active external event flag. Based on this distribution, the normal/abnormal threshold was set at a two-flag average for each event type. Only one external variable required a flag per TMC average greater than two. Based on this criterion, speed distributions were generated for normal and abnormal conditions over each temporal analysis period. Table I-B - 31 lists the speed distributions observed along Route 1 EB. Table I-B - 32 shows statistical data and critical percentiles for the route.

Table I-B - 29: Route 1 EB characteristics and associated TMC segment descriptions

	I-40 EB	I-540 EB	Entire Route
Number of TMC Segments	8	16	24
Total distance of TMCs (mi)	2.9244	16.0808	19.0052
First TMC Segment	125-04866	125+04987	125-04866
Last TMC Segment	125N04863	125P05083	125P05083

Table I-B- 30: Route 1 EB event flag distributions for incidents, flow rates, and weather for all temporal intervals

Number of Flags	Incidents Only	Weather Only	Flow Only	F & I	F & W	I & W	All
> 0	3951	13758	332	2	19	387	0
> 1	3785	12250	98	0	4	346	0
> 2	3246	12215	15	0	1	282	0
> 3	3211	12198	1	0	0	271	0
> 4	3059	12178	0	0	0	241	0
> 5	2182	12038	0	0	0	191	0
Average	**5.1680**	**19.0391**	**0.8642**				

Table I-B - 31: Route 1 EB speed distribution for both normal and abnormal operating conditions for each temporal analysis period

	24-Hour	AM Peak	PM Peak	Off-Peak	Weekend
Normal					
60+	6.50%	9.43%	8.42%	5.47%	5.72%
55-60	87.84%	89.15%	68.39%	91.77%	92.46%
45-55	3.25%	1.27%	10.52%	2.11%	1.65%
40-55	1.18%	0.09%	6.05%	0.35%	0.10%
30-40	0.92%	0.03%	5.03%	0.20%	0.05%
15-30	0.30%	0.03%	1.53%	0.09%	0.02%
0-15	0.01%	0.00%	0.07%	0.00%	0.00%
Abnormal					
60+	4.89%	8.54%	7.07%	3.99%	4.71%
55-60	87.25%	87.37%	68.96%	89.27%	87.80%
45-55	5.19%	2.83%	9.17%	4.80%	5.88%
40-55	1.05%	0.50%	3.72%	0.88%	0.91%
30-40	0.95%	0.25%	3.53%	0.91%	0.65%
15-30	0.59%	0.50%	6.40%	0.15%	0.05%
0-15	0.08%	0.00%	1.15%	0.00%	0.00%

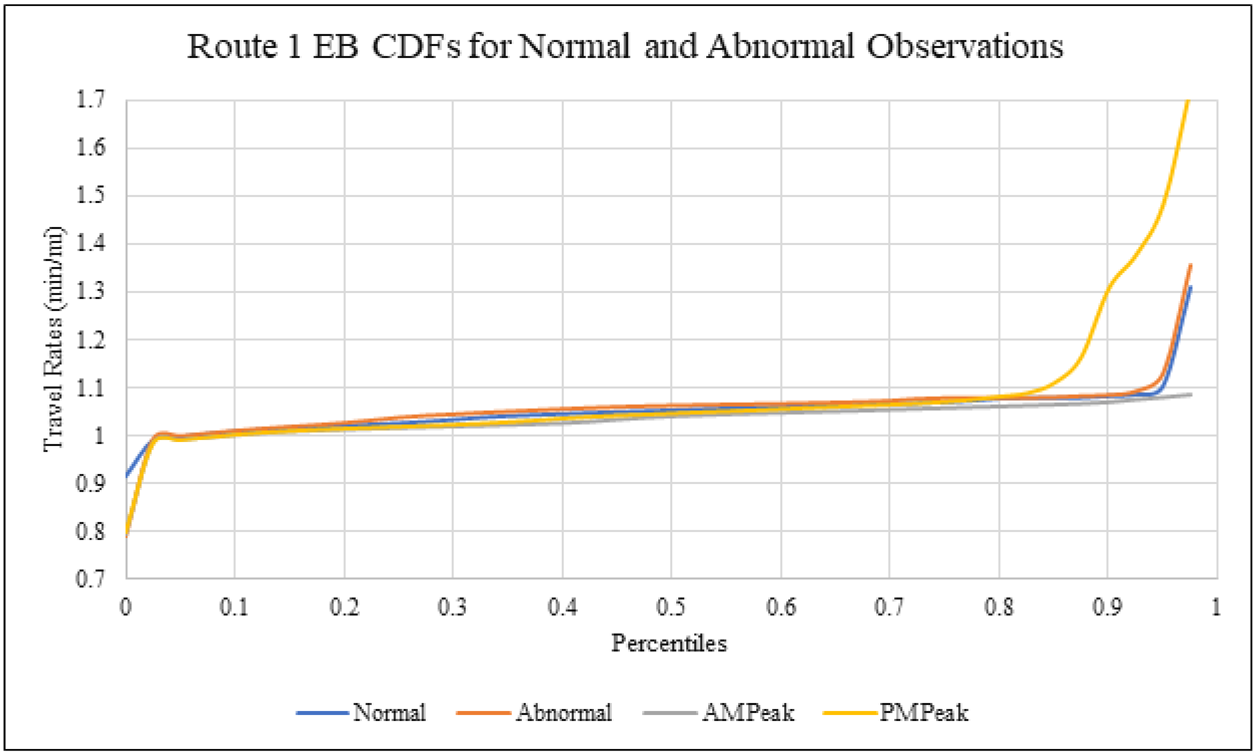
Table I-B - 32: Statistical data and critical percentiles for Route 1 EB

	Normal	Abnormal	Normal AM	Normal PM
Mean Travel Rate	1.0643	1.0800	1.0394	1.1066
Mean S.D.	0.1050	0.1858	0.0362	0.2357
# of Deviant Obs	2996	0	121	898
Percentiles / Travel Rate				
0.05	0.9985	1.0002	0.9926	0.9917
0.25	1.0265	1.0389	1.0181	1.0200
0.5	1.0539	1.0639	1.0422	1.0477
0.75	1.0707	1.0794	1.0593	1.0713
0.95	1.1053	1.1319	1.0818	1.4815
Buffer Time Index	0.0488	0.0639	0.0379	0.4140

The speed distribution along this route indicated poor performance across all time periods with the majority of vehicle speed observations were between 55-60 mph. This result suggests the presence of recurring congestion and likely capacity deficiencies. The normal PM peak period buffer time index was substantially higher than the other three analysis conditions.

Exhibit I-B - 25 displays CDF functions for Route 1 EB travel rates for both normal and abnormal observations. The normal observation PM peak period distribution indicated the sharpest increase in variability, while the normal AM peak period distribution was the flattest of the four analysis scenarios.

Exhibit I-B - 25: CDF plots of normal and abnormal conditions for Route 1 EB and normal AM and PM peak period distribution plots



Route 2 WB Analysis – I-440 & US 64 Bus to I-40 & Davis Dr. (RTP)

This route was comprised of TMCs from I-440 WB, all TMCs along Wade Avenue WB, and some TMCs along I-40 WB from US 64 Bus in east Raleigh to Davis Dr. near RTP. Table I-B - 33 shows information about the route and the TMCs that comprise it. Table I-B - 34 shows the distribution of temporal route observations by the number of TMCs along the route with an active external event flag. Based on this distribution, the normal/abnormal threshold was set at a two-flag average for each event type. Based on these criteria, speed distributions were generated for normal and abnormal conditions over each temporal analysis period. Table I-B - 35 lists the speed distributions observed along Route 2 WB. Valid travel time/speed data was only available for approximately half of the 105120 temporal observation intervals. Therefore, the sample size for these analyses are significantly smaller than other route and facility analyses. Table I-B - 36 shows statistical information on the route, including critical percentiles, mean, standard deviation, and buffer time index.

Table I-B - 33: Route 2 WB characteristics and associated TMC segment descriptions

	I-440 WB	Wade Ave WB	I-40 WB	Entire Route
Number of TMC Segments	18	6	14	38
Total distance of TMCs (mi)	10.2194	2.2784	8.4769	20.9747
First TMC Segment	125+04986	125P10249	125+04860	125+04986
Last TMC Segment	125P04980	125+04970	125P04866	125P04866

Table I-B - 34: Route 2 WB event flag distributions for incidents, flow rates, and weather for all temporal intervals

Number of Flags	Flow Only	Incidents Only	Weather Only	F & I	F & W	I & W	All
> 0	1413	2151	13444	96	120	184	15
> 1	734	963	7105	31	65	95	2
> 2	521	183	6665	3	42	6	0
> 3	370	83	6602	0	27	3	0
> 4	253	35	6523	0	19	2	0
> 5	253	17	6166	0	8	0	0
Average	**2.0853**	**0.9989**	**13.6840**				

Table I-B - 35: Route 2 WB speed distribution for both normal and abnormal operating conditions for each temporal analysis period

	24-Hour	AM Peak	PM Peak	Off-Peak	Weekend
Normal					
60+	82.58%	73.36%	63.64%	89.50%	85.38%
55-60	11.15%	11.81%	14.34%	9.34%	11.95%
45-55	3.15%	7.42%	10.19%	0.77%	1.52%
40-55	0.87%	2.20%	2.76%	0.15%	0.50%
30-40	1.13%	2.66%	4.01%	0.16%	0.53%
15-30	1.08%	2.41%	4.89%	0.08%	0.13%
0-15	0.04%	0.12%	0.16%	0.00%	0.00%
Abnormal					
60+	76.32%	54.50%	60.27%	86.22%	82.42%
55-60	15.32%	23.46%	15.10%	12.67%	14.44%
45-55	3.98%	12.89%	7.26%	0.64%	1.77%
40-55	1.16%	4.05%	2.61%	0.11%	0.08%
30-40	1.50%	3.75%	4.09%	0.25%	0.89%
15-30	1.64%	1.35%	10.10%	0.11%	0.40%
0-15	0.07%	0.00%	0.57%	0.00%	0.00%

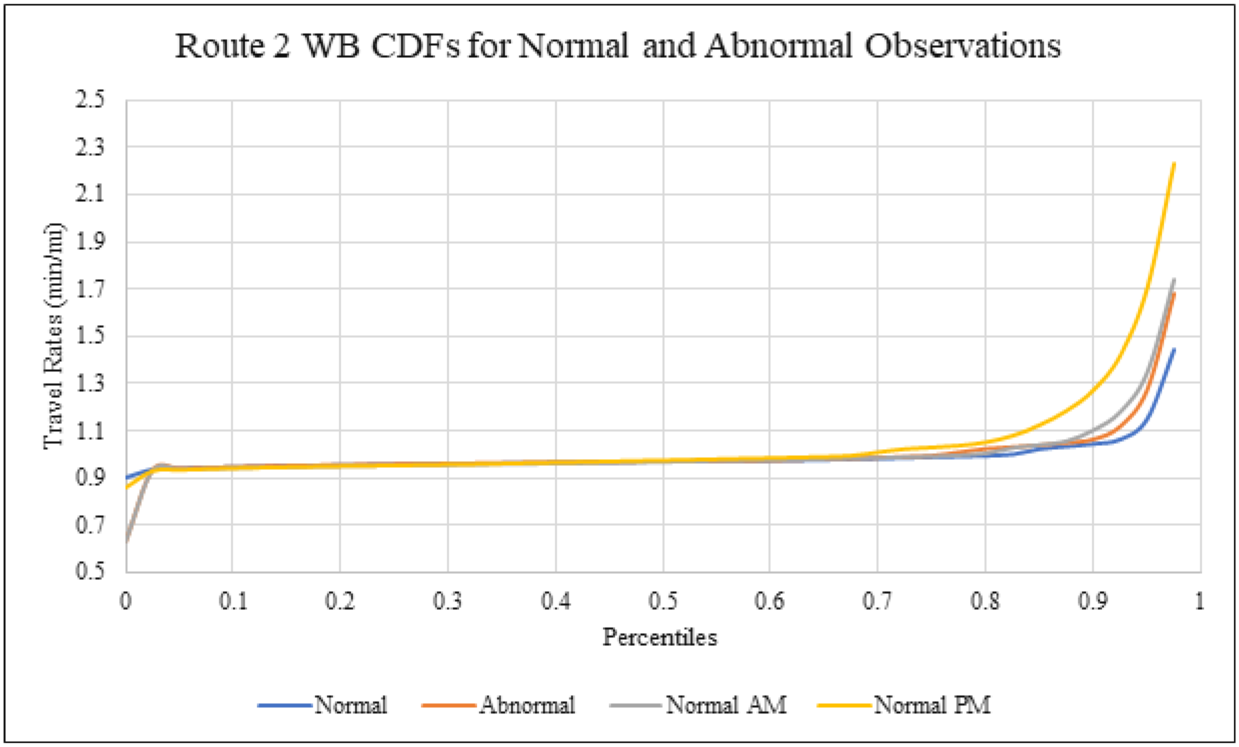
Table I-B - 36: Statistical data and critical percentiles for Route 2 WB

	Normal	Abnormal	Normal AM	Normal PM
Mean Travel Rate	1.0106	1.0324	1.0305	1.0871
Mean S.D.	0.2110	0.2688	0.2630	0.3621
# of Deviant Obs	1134	203	223	421
Percentiles / Travel Rate				
0.05	0.9397	0.9409	0.9354	0.9380
0.25	0.9568	0.9593	0.9516	0.9568
0.5	0.9693	0.9706	0.9669	0.9785
0.75	0.9870	0.9956	0.9898	1.0325
0.95	1.1486	1.2756	1.3457	1.7046
Buffer Time Index	**0.1849**	**0.3141**	**0.3918**	**0.7421**

For normal observations, the PM peak period had the lowest proportion of vehicle speeds higher than 60+ miles per hour. The AM peak period had the lowest proportion of vehicle speeds higher than 60+ miles per hour for abnormal observations. For all temporal analysis periods, the abnormal speed distribution was at least a few percentage points below the normal observations.

Exhibit I-B - 26 shows CDF functions for Route 2 WB travel rates for both normal and abnormal observations. The normal observation PM peak period distribution indicated the highest variation toward the upper end of the distribution. The normal observation AM peak period had more variation relative to the 24-hour normal observation distribution in addition to higher travel rates at the high end of the distribution.

Exhibit I-B - 26: CDF plots of normal and abnormal conditions for Route 2 WB and normal AM and PM peak period distribution plots



Route 2 EB Analysis – I-40 & Davis Dr. (RTP) to I-440 & US 64 Bus

This route was constructed from TMC segments along I-440 EB, Wade Ave EB, and I-440 EB. Table I-B - 37 displays information about the route and the component TMCs. Table I-B - 38 shows the distribution of temporal route observations by the number of TMCs along the route with an active external event flag. Based on the results of this analysis, the normal/abnormal threshold was set at a two-flag average for each event type. For these criteria, speed distributions were generated for both normal and abnormal conditions during each temporal analysis period. Table I-B - 39 displays the generated speed distributions observed along Route 2 EB. Valid vehicle probe data was only available for about half of the temporal intervals during 2010. Therefore, the sample of constructed route travel rates significantly smaller than other routes and facility analyses. Table I-B - 40 shows statistical information on the route, including critical percentiles, mean, standard deviation, and buffer time index.

Table I-B - 37: Route 2 EB characteristics and associated TMC segment descriptions

	I-440 EB	Wade Ave EB	I-40 EB	Entire Route
Number of TMC Segments	17	6	14	37
Total distance of TMCs (mi)	9.2519	2.3296	8.3455	19.9270
First TMC Segment	125N04980	125-04969	125N04866	125N04866
Last TMC Segment	125N04986	125N04967	125-04859	125N04986

Table I-B - 38: Route 2 WB event flag distributions for incidents, flow rates, and weather for all temporal intervals

Number of Flags	Flow Only	Incidents Only	Weather Only	F & I	F & W	I & W	All
> 0	1848	5651	14546	63	129	759	2
> 1	421	5047	13831	11	31	649	0
> 2	169	3565	13723	0	13	329	0
> 3	57	3420	13625	0	2	305	0
> 4	16	2457	13555	0	1	255	0
> 5	16	2401	12492	0	0	251	0
Average	**0.9121**	**4.4266**	**19.1895**				

Table I-B - 39: Route 2 EB speed distribution for both normal and abnormal operating conditions for each temporal analysis period

	24-Hour	AM Peak	PM Peak	Off-Peak	Weekend
Normal					
60+	82.58%	73.36%	63.64%	89.50%	85.38%
55-60	11.15%	11.81%	14.34%	9.34%	11.95%
45-55	3.15%	7.42%	10.19%	0.77%	1.52%
40-55	0.87%	2.20%	2.76%	0.15%	0.50%
30-40	1.13%	2.66%	4.01%	0.16%	0.53%
15-30	1.08%	2.41%	4.89%	0.08%	0.13%
0-15	0.04%	0.12%	0.16%	0.00%	0.00%
Abnormal					
60+	76.32%	54.50%	60.27%	86.22%	82.42%
55-60	15.32%	23.46%	15.10%	12.67%	14.44%
45-55	3.98%	12.89%	7.26%	0.64%	1.77%
40-55	1.16%	4.05%	2.61%	0.11%	0.08%
30-40	1.50%	3.75%	4.09%	0.25%	0.89%
15-30	1.64%	1.35%	10.10%	0.11%	0.40%
0-15	0.07%	0.00%	0.57%	0.00%	0.00%

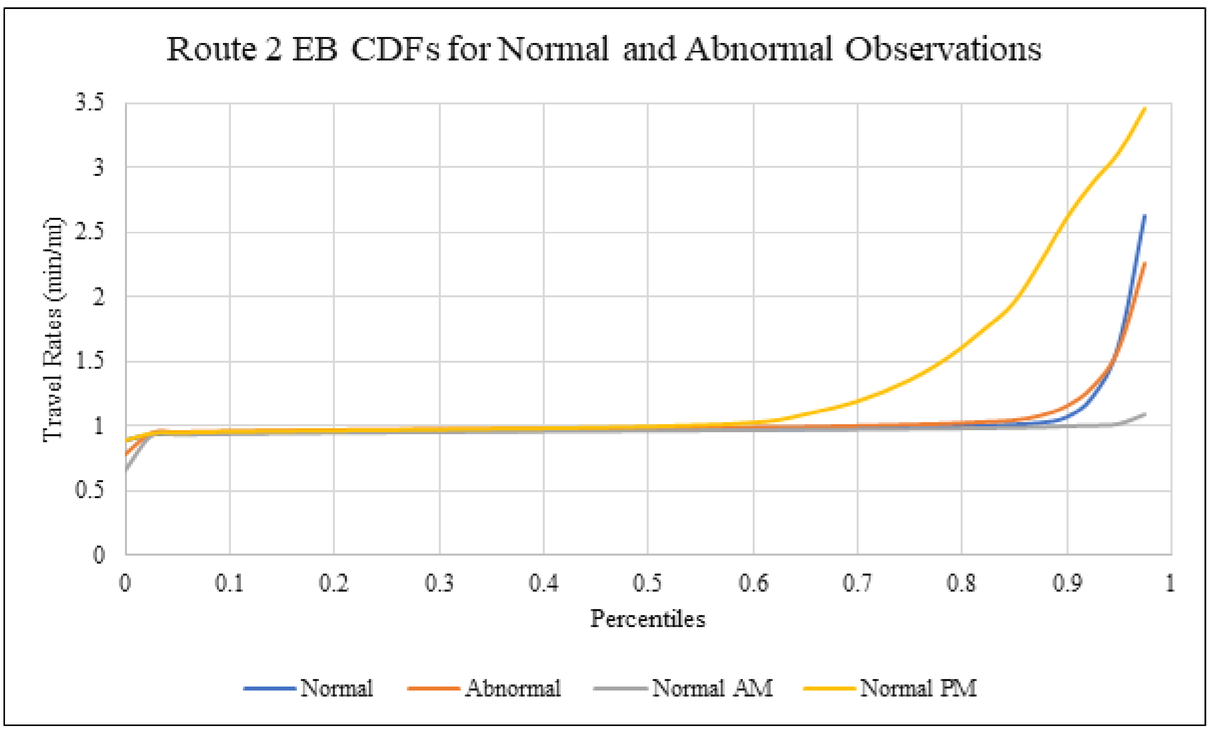
Table I-B - 40: Statistical data and critical percentiles for Route 2 EB

	Normal	Abnormal	Normal AM	Normal PM
Mean Travel Rate	1.0106	1.0324	1.0305	1.0871
Mean S.D.	0.2110	0.2688	0.2630	0.3621
# of Deviant Obs	1713	369	59	770
Percentiles / Travel Rate				
0.05	0.9425	0.9456	0.9322	0.9462
0.25	0.9609	0.9653	0.9515	0.9660
0.5	0.9739	0.9764	0.9641	0.9920
0.75	0.9902	1.0037	0.9787	1.3527
0.95	1.6261	1.5923	1.0192	3.1082
Buffer Time Index	**0.6696**	**0.6308**	**0.0571**	**2.1332**

For all temporal observations, there was an approximately 6% decrease in observed speeds greater than 60 mph from normal conditions to abnormal conditions. During normal conditions, the PM peak period reported the lowest proportion of speeds greater than 60 mph. However, during abnormal conditions, the AM peak period experienced the lowest proportion of speeds greater than 60 mph. For this route direction, there was an inverse relationship between absolute travel rate and variability across each temporal analysis period and observation type. The 24-hour normal observation buffer time index was higher than normal observations during the AM peak period.

Exhibit I-B - 27 displays CDF functions for Route 2 EB travel rates for both normal and abnormal observations. The normal and abnormal distributions generally tracked each other, suggesting that average rates calculated over an entire route even out some of the impact generated by external events. The AM peak period indicates that speeds started to fall below 60 mph at the 60th percentile compared to the 85th percentile for the 24-hour distributions, which validates the lower buffer time index. Even though speeds decrease during the PM peak period as indicated by the speed distribution, the normal observation PM distribution did not sharply increase at the upper end of the distribution.

Exhibit I-B - 27: CDF plots of normal and abnormal conditions for Route 2 EB and normal AM and PM peak period distribution plots

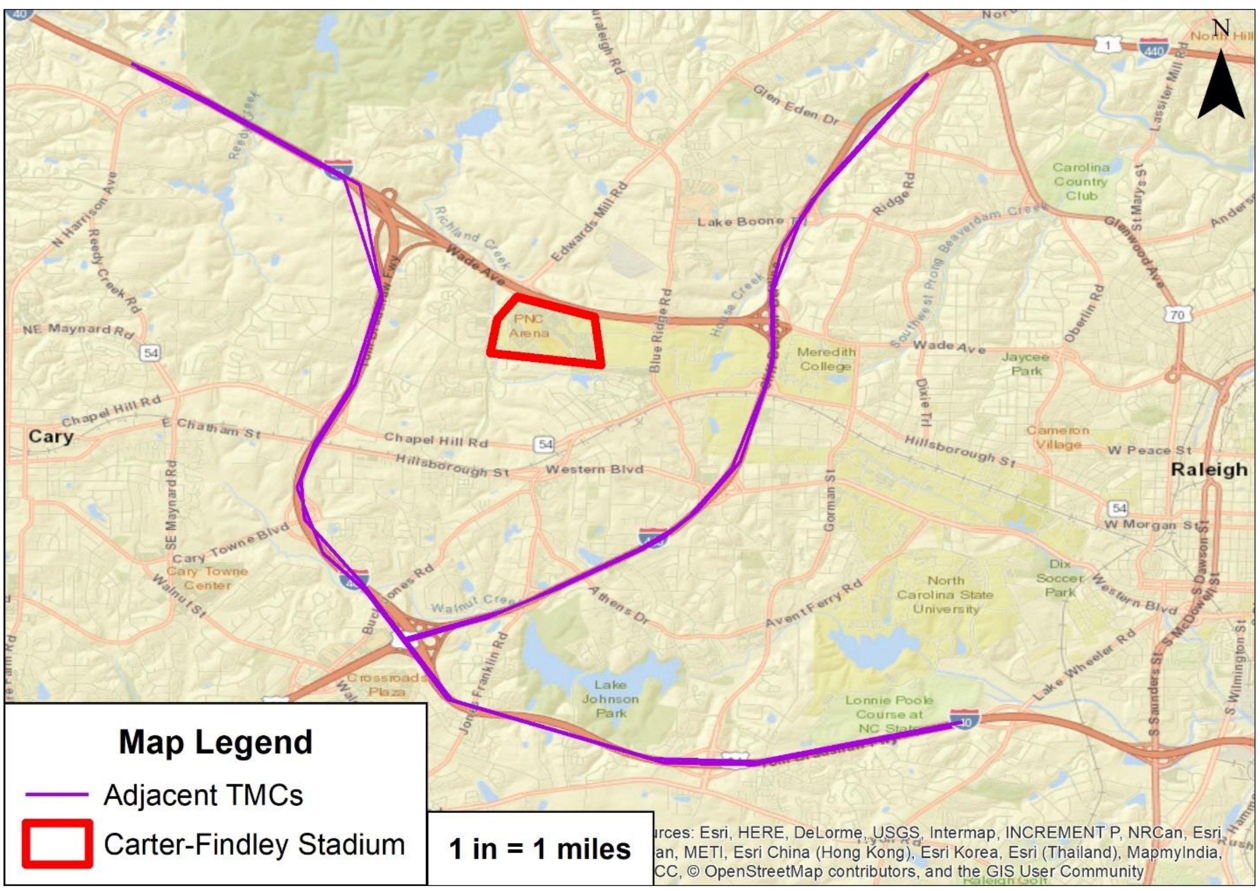


Special Event Analysis

The only special demand-generating event identified during the 2010 study year was a Thursday-night NC State home football game held at Carter-Finley Stadium, the university's off-campus football venue, on September 16th. The football game started at 7:30 PM. However, fans began arriving in the parking lots earlier in the afternoon. For the purpose of reliability analysis, the start of the event analysis period was set at 4:00 PM. The event analysis period ended at 10:00 PM. This temporal window shows the entire weekday evening peak period. The stadium is located adjacent to the Wade Avenue extension and in the vicinity of I-40 and I-440, therefore gameday traffic interacted with typical evening rush hour traffic and likely increased travel times near the stadium. By the end of the game, background traffic was likely significantly lower and departing fans were more easily absorbed into the freeway traffic streams.

Exhibit I-B - 28 indicates the location of the stadium and adjacent TMCs that were analyzed to determine possible impacts on facility direction and commuting routes. Determination of which public events occurring during the study year constitute special demand-generating events was the responsibility of the analyst based on the purpose and objectives of the analysis and local knowledge about such events and adjacent facilities. Other mass-gathering events occurred during the 2010 study year, however, adjacent facilities can typically handle the additional demand. Congestion may be present but limited to local streets used to access the venue.

Exhibit I-B - 28: Location of football stadium and TMCs included in the event analysis.



Wade Avenue was not included in the analysis because this facility primarily provides access to the stadium, adjacent arena, and state fairgrounds. Commuters that typically utilize the Wade Avenue extension on weekday evenings likely chose alternative routes to avoid gameday traffic. However, I-40 and I-440 continued to serve commuter traffic and were susceptible to major impacts on the traffic stream. A spatial selection was performed in GIS to develop a list of TMCs in the immediate vicinity of the stadium that could have outsized traffic demand due to the football game. Traffic along US 1 south of I-440 was also likely impacted, however, that facility was not among those in this study.

Twelve TMC segments were identified as likely impacted for both directions of I-40 and 13 TMC segments were identified for both directions of I-440. Travel rate data, deviant time/space observations, means, and percentile data were retrieved from the facility direction datasets. Deviant time/space regions without associated external events as defined by the facility PM peak period mean and standard deviation were identified for each TMC during the event temporal analysis period. Travel rates without any external event flags were classified as deviant if outside of two standard deviations on either side of the mean. While the last two hours of the event analysis period were outside of the facility PM peak period, the PM means and standard deviations for each TMC segment were used for all time intervals.

I-40 EB TMC segments located near the stadium reported 68 normal deviant observations during the event temporal analysis period. 125-04859 and 125N04859 both reported the highest number of deviant five-minute temporal intervals at 12. 9.87 miles of I-40 EB was included in the event analysis area, the longest of any facility direction in the vicinity of the stadium. The mean travel rates were tabulated for each TMC from 4:00 PM to 8:00 PM on the day of the event and compared to the PM peak facility means for the entire year. On average TMC means during the special events were 0.076 minutes per mile higher than the PM peak facility mean. The highest increase, 0.242 minutes per mile, occurred along the 125N04859 segment. The difference in means for each I-40 EB TMC was less than one standard deviation.

Exhibit I-B - 29 plots 5-minute aggregated travel rates over the event temporal analysis period for several I-40 EB TMCs, namely 125N04860, 125-04859, 125-04857,125N04857, 125-04965, and 125N04965. Table I-B - 38 contains information about the TMCs along I-40 EB in the vicinity of the stadium.

Exhibit I-B - 29: Travel Rates for selected I-40 EB TMCs during special event

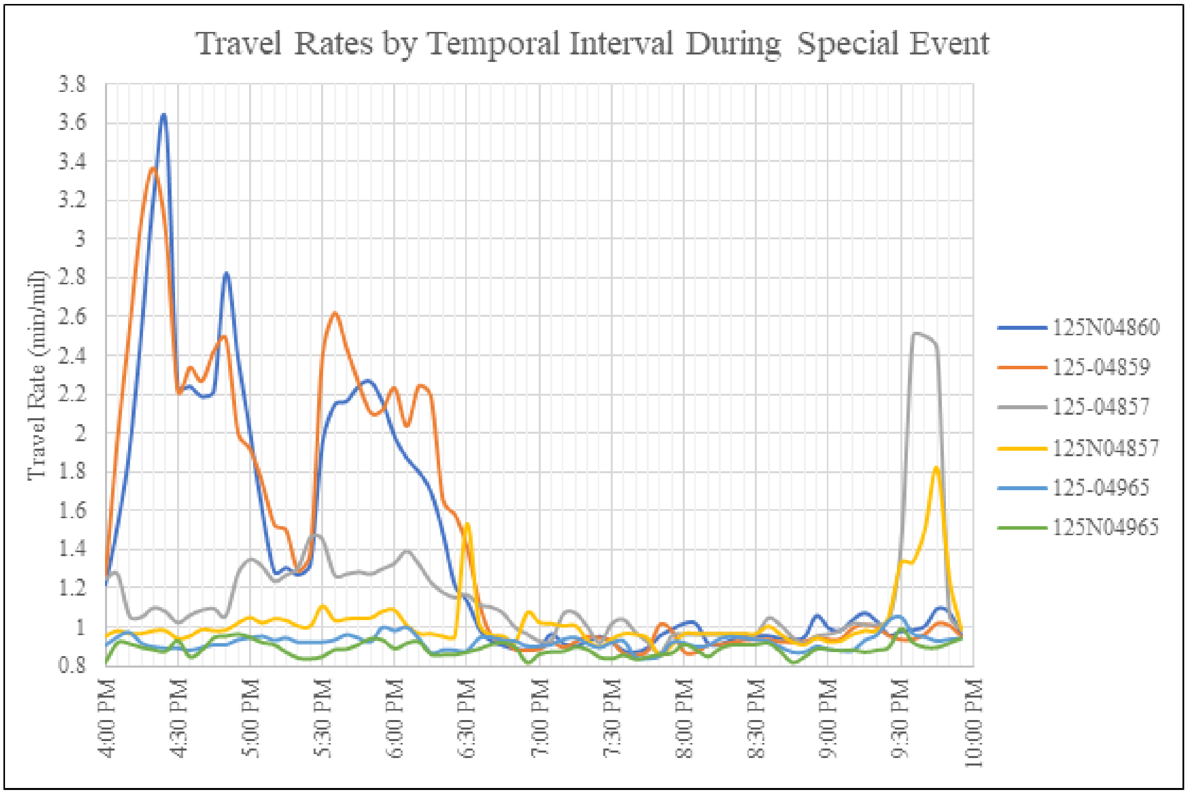
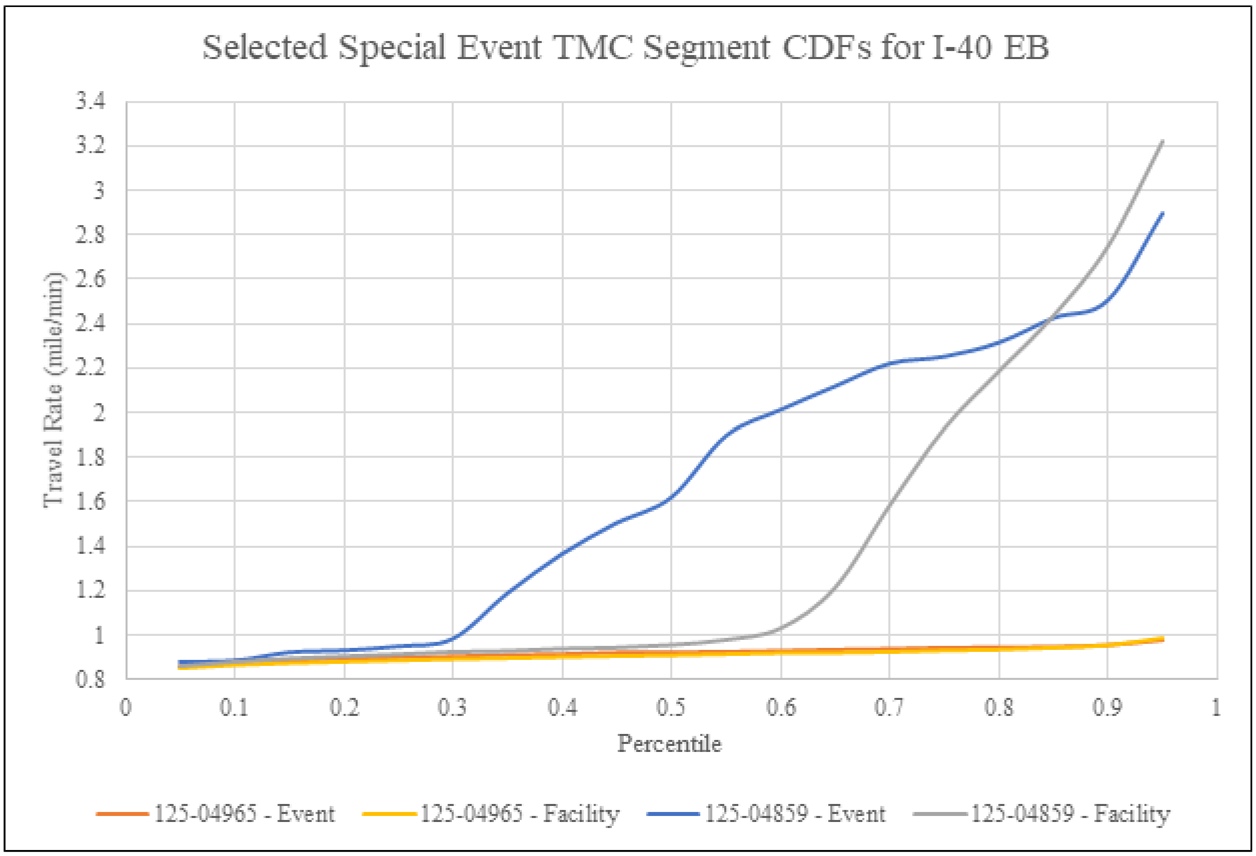


Table I-B - 41: Description of TMC segments along I-40 EB included in the event study area

TMC Segment	Nearest Interchange	Length (miles)	Mean Event PM Peak Travel Rate	Number of Deviant Intervals
125N04860	Harrison Ave	0.548	1.5965	6
125-04859	Wade Ave Ext	1.083	1.6997	12
125N04859	Wade Ave Ext	1.063	1.6129	12
125-04858	NC-54 / Cary	0.783	1.4310	6
125N04858	NC-54 / Cary	0.519	1.4654	10
125-04857	Cary Town Blvd	0.378	1.1480	3
125N04857	Cary Town Blvd	0.571	1.0039	1
125-04856	I-440/US 1 / 64	0.402	0.9812	2
125N04856	I-440/US 1 / 64	1.064	1.0345	8
125-04965	Gorman St.	1.531	0.9213	0
125N04965	Gorman St.	0.598	0.8992	0
125-04964	Lake Wheeler Rd.	1.332	0.8849	0
TOTALS:		**9.87335**		**68**

Exhibit I-B - 30 shows CDF plots for two TMCs in the I-40 EB event study area using the travel rates during the PM peak period on the day of the special event and travel rates from every weekday PM peak period during the 2010 study year. The PM peak period facility CDFs of 125-04859, a TMC located west of the stadium, and 125-04965, a TMC to the east of the stadium, were compared with a CDF plot based on the travel rates reported during the event temporal analysis period for each TMC. The median travel rate during the event for 125-04859 was significantly higher than the median travel rate over all weekday PM peak periods during the study year. However, the 95th percentile travel rate for all PM peaks was higher than the event-based distribution. This suggests that some users recognized the potential for delays and chose alternative routes once travel rates start drastically increasing. 125-04859 had buffer time indices of 0.7826 and 2.3747 for the event analysis period and all PM peak periods in 2010 respectively. 125-04965 had a PM peak buffer time index of 0.0847 and an event temporal period buffer time index of 0.0590.

Exhibit I-B - 30: CDF plots for two TMCs along I-40 EB in event spatial and temporal interview



I-40 WB TMCs in the event spatial study area reported 135 deviant observations based on the PM peak period mean and standard deviation for the facility direction. 125+04965 reported the highest number of deviant observations, 25. On average, I-40 WB TMCs had a mean travel rate during the event analysis period that was 0.027 min/mi higher than the mean travel rates for all PM peak periods in 2010. Exhibit I-B - 31 shows travel rate plots for TMC segments 125P-4965, 125+04966, 125+04859, and 125P04859. At 5:15 PM and again at 5:30 PM, a sharp peak in travel rate was observed in 125+04966. Later in the event analysis period, at 8:30 PM, 125P04859 experienced a spike in travel rate. 125+04859 had a concurrent spike in travel rates of a smaller magnitude. 125P04965 peaked at 5:35 PM and 6:05 PM. However, the peak travel rate was significantly lower than 125+04966. Table I-B - 42 shows information on TMC segments along I-40 WB included in the event spatial study area.

Exhibit I-B - 31: Travel rates during special event temporal analysis period for selected I-40 WB TMC segments in the event spatial area

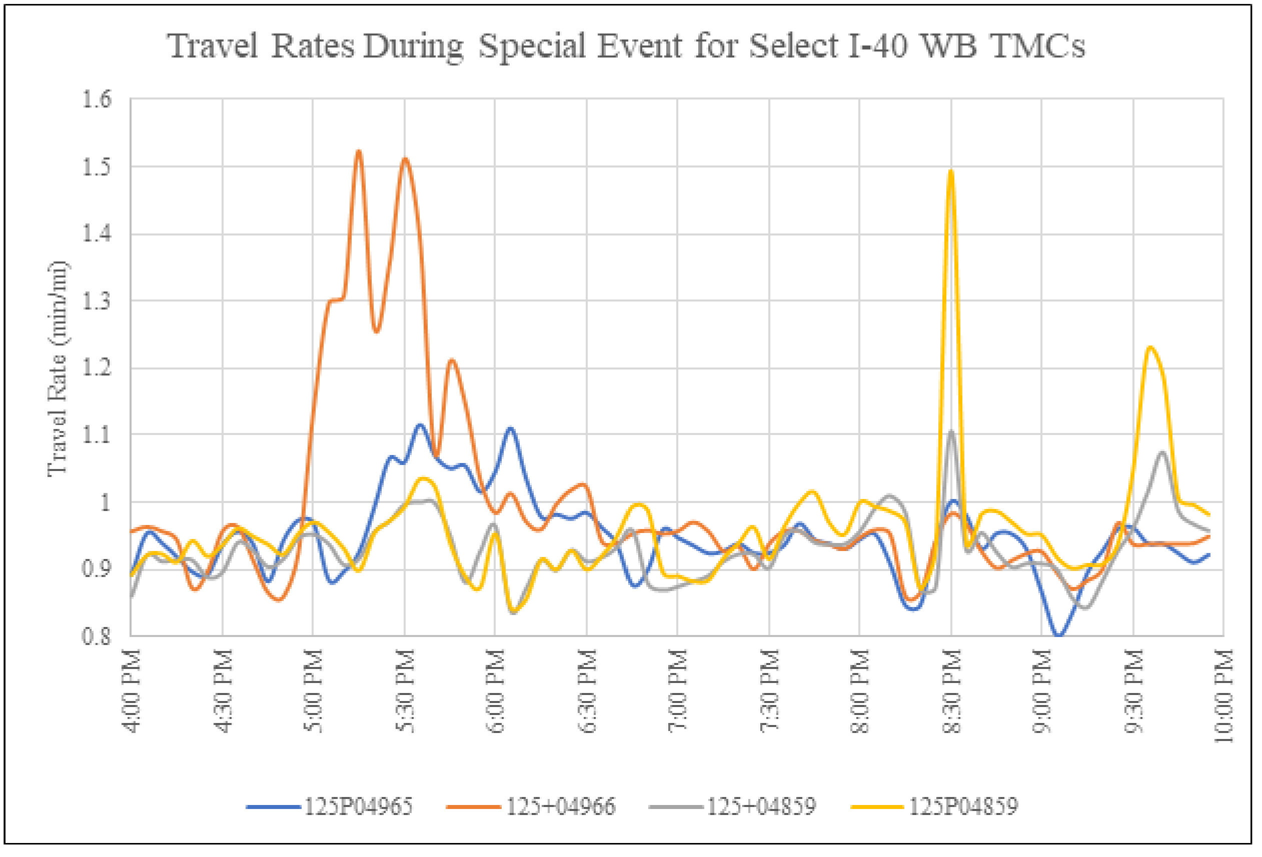
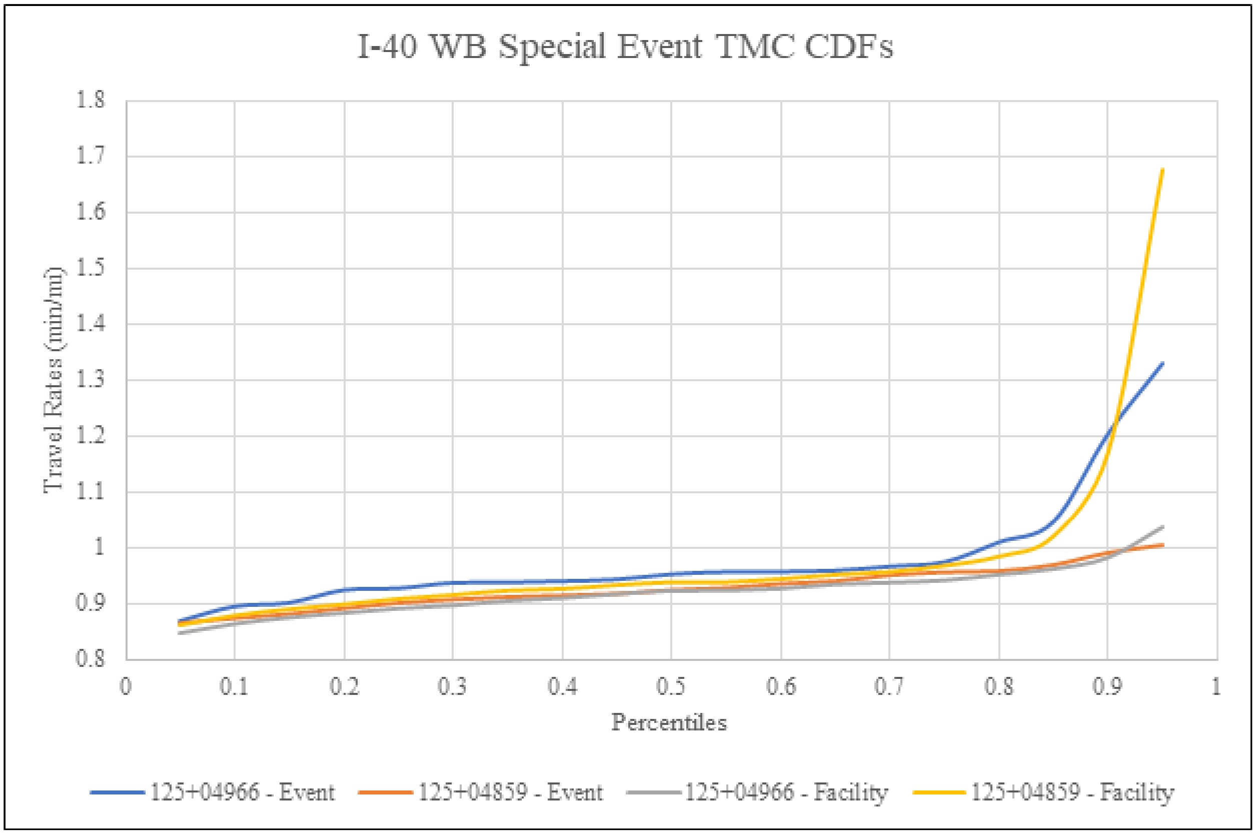


Table I-B - 42: Description of TMC Segments along I-40 WB within the event analysis area

TMC Segment	Nearest Interchange	Length (miles)	Mean Event PM Peak Travel Rate	Number of Deviant Intervals
125+04965	Gorman St.	1.3827	1.1436	25
125P04965	Gorman St.	0.6926	0.9615	19
125+04966	US 64 / US 1	1.4222	1.0279	10
125P04966	US 64 / US 1	1.1002	1.1064	6
125P04856	US 1/64/I-440	1.1002	1.1401	7
125+04857	Cary Towne Blvd	0.6841	0.9625	0
125P04857	Cary Towne Blvd	0.3270	1.0144	8
125+04858	NC -54 / Cary	0.2662	1.0116	8
125P04858	NC -54 / Cary	0.5929	1.0151	12
125+04859	Wade Ave Ext	0.7160	0.9220	10
125P04859	Wade Ave Ext	1.0111	0.9358	6
125+04860	Harrison Ave.	1.1875	0.9666	12
125P04860	Harrison Ave.	0.6064	0.8990	12
TOTALS:		**9.3824**		**135**

CDFs of all weekday PM peak periods and the event PM peak period were generated for 125+04966 and 125+04859. The plots of each distribution are shown in Exhibit I-B - 32. For these I-40 WB TMCs, the 95th percentile travel rate is higher for the distribution of all PM peak periods than the event peak period. 125+04966 had a buffer time index of 0.788 based on all peak periods and a buffer time index of 0.3964 based on the event temporal travel rate observations. 125+04859 had buffer time indices of 0.124 and 0.086 for all PM peak periods and the event analysis period respectively.

Exhibit I-B - 32: CDFs of selected I-40 WB TMC segments over all PM peak periods and the event analysis period



Only one TMC along I-440 EB among the spatial segments included in the event analysis reported a deviant time/space travel rate based on the mean and standard deviation over all PM peak periods of 2010. 125N04982 reported a single deviant observation at 5:25 PM. Among I-440 EB TMCs in the event spatial analysis area, the average difference in event and PM peak period means was -0.02 mins per mile. Exhibit I-B - 33 shows the travel rates for selected TMCs along I-440 EB. Table I-B - 43 contains descriptions and other metrics on the TMCs on I-440 EB within the event spatial areas.

Exhibit I-B - 33: Travel rates during the temporal event analysis period for selected I-440 EB TMC segments

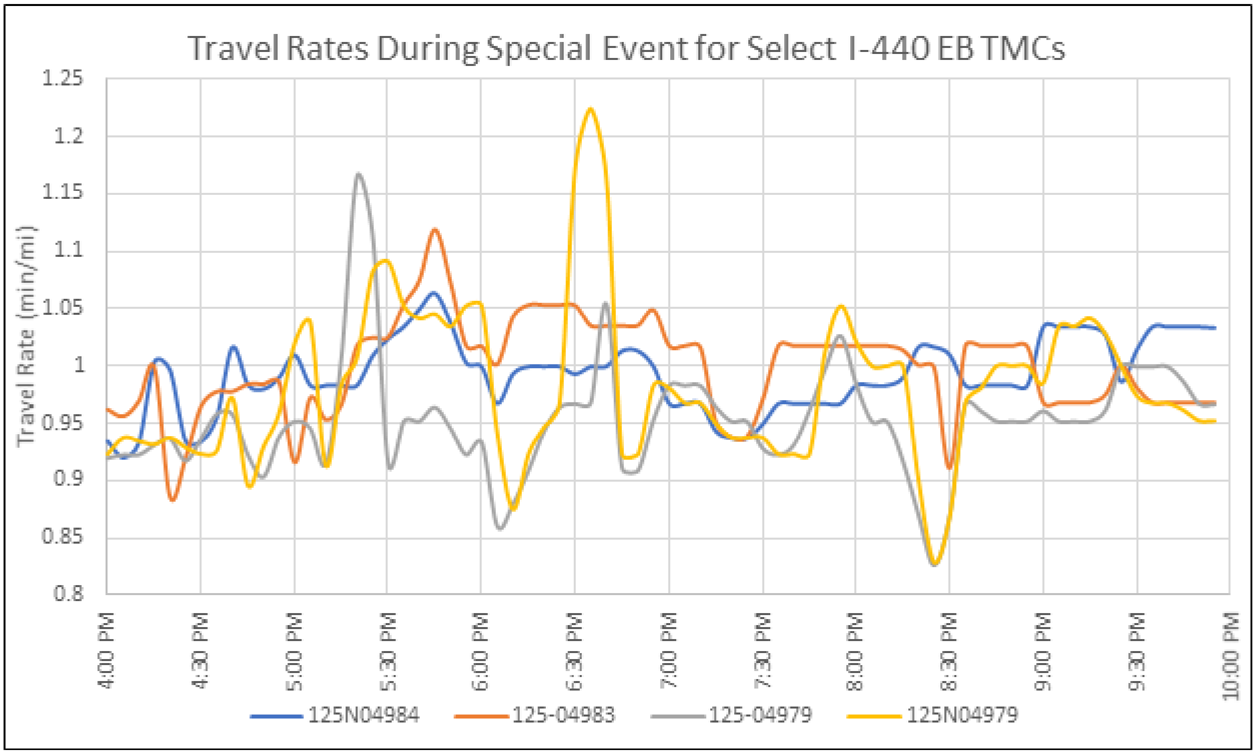
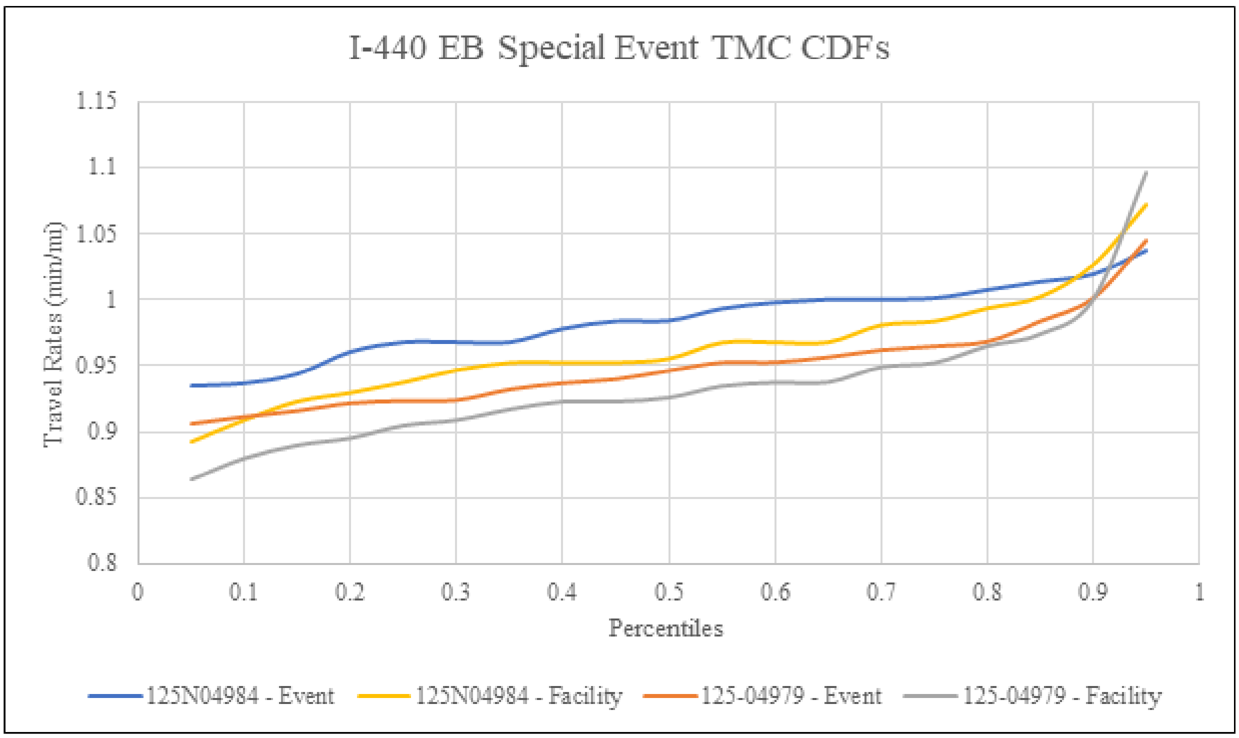


Table I-B - 43: Description of I-440 EB TMC segments in the event spatial study area

TMC Segment	Nearest Interchange	Length (miles)	Mean Event PM Peak Travel Rate	Number of Deviant Intervals
125-04984	Jones Franklin Rd.	0.1310	0.9768	0
125N04984	Jones Franklin Rd.	0.5353	0.9929	0
125-04983	Melbourne Rd.	0.6243	0.9983	0
125N04983	Melbourne Rd.	0.1858	0.9810	0
125-04982	Western Blvd.	0.3140	1.0110	0
125N04982	Western Blvd.	0.4853	1.0222	0
125-04981	Hillsborough St. (NC 54)	0.6320	1.0644	1
125N04981	Hillsborough St. (NC 54)	0.1795	1.0234	0
125-04980	Wade Avenue	0.1013	1.0323	0
125N04980	Wade Avenue	0.5082	1.0075	0
125-04979	Lake Boone Trail	0.5832	0.9534	0
125N04979	Lake Boone Trail	0.3491	0.9811	0
125-04978	Ridge Rd	1.0446	0.9707	0
TOTALS:		**5.6733**		**1**

Exhibit I-B - 34 shows CDF plots for 125N04984 and 125-04979 corresponding to event analysis period data and facility data for every PM peak weekday period in 2010. For both TMC segments, the event distribution generally had higher rates than the facility distributions based on a year's worth of data. However, the 95th percentile was higher for both facility distribution. The larger time horizon incorporated into the facility distribution may have captured significantly deviant travel rate observations above and beyond the impacts of the special event. 125N04984 had an event buffer time index of 0.0835 and a facility buffer time index of 0.1301. 125-04979 experienced an event buffer time index of 0.1044 and a facility buffer time index of 0.1929.

Exhibit I-B - 34: CDF plots of selected I-440 EB TMCs in the event spatial area.



A total of 34 time/space observations along I-440 WB TMCs in the event spatial study area were deviant based on the PM peak period mean and standard deviation. 125P04982 reported the highest number of deviant time/space observations with 7. On average, the event mean was 0.092 min/mi lower than then the facility means. Exhibit I-B - 35 shows a plot of travel rates for several I-440 WB TMCs in the event study area over the temporal analysis period. 125P04979 and 125+04980 experienced a significant spike in travel rates at approximately 5:30 PM. 125+04980 had a secondary peak at 6:00 PM. These TMC segments are located near the I-440 and Wade Ave. interchange, a primary access point for fans driving to the stadium. The other TMC segments are near the Jones Franklin Rd. interchange, a segment of I-440 WB not expected to carry event-related traffic.

Exhibit I-B - 35: Travel rates for selected I-440 WB TMC segments in the event spatial analysis area

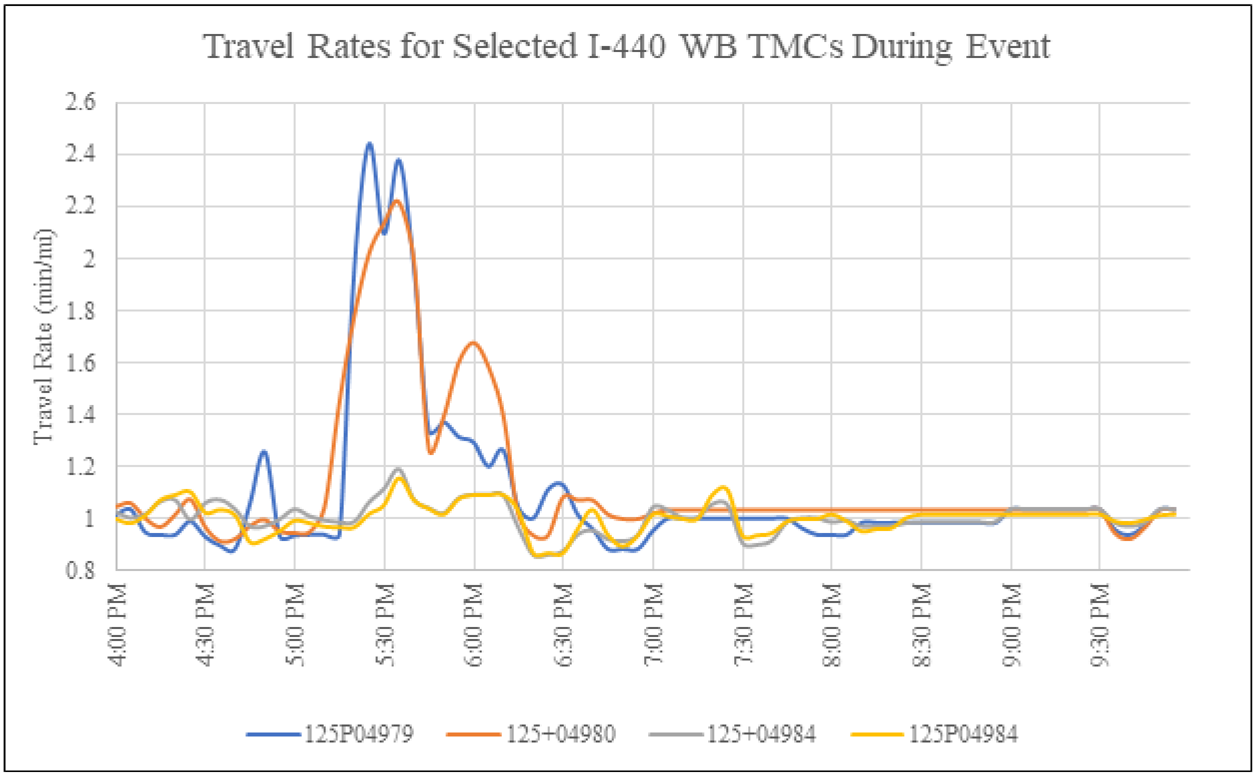


Table I-B - 44 contains TMC descriptions and other metrics for the I-440 WB TMC segments included in the event analysis area.

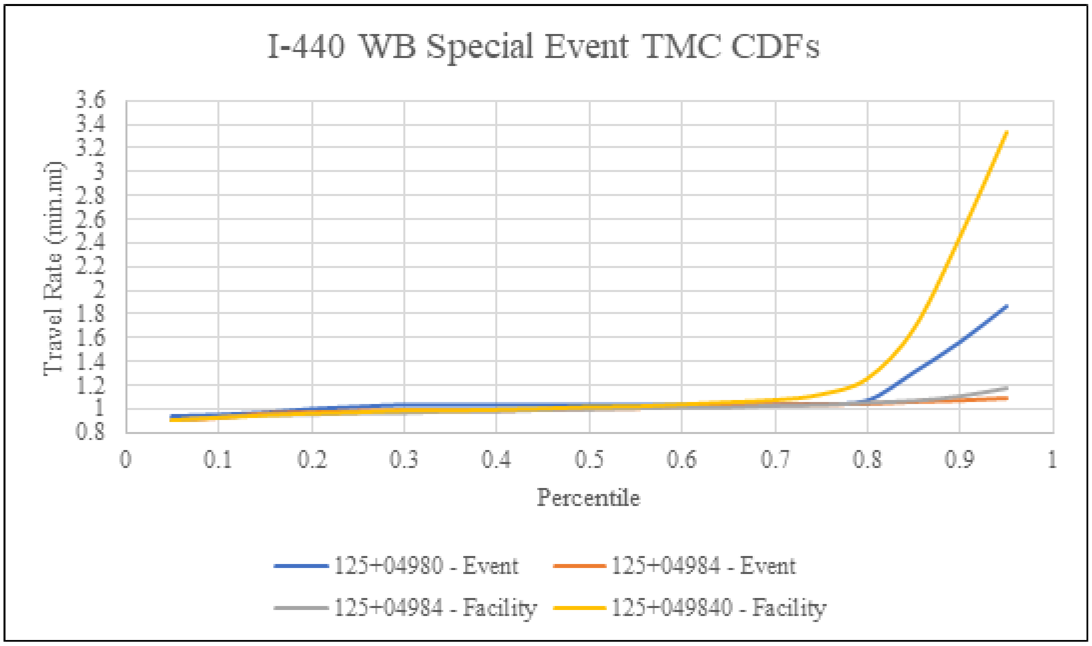
Table I-B - 44: Description of I-440 WB TMC segments located within the event analysis area.

TMC Segment	Nearest Interchange	Length (miles)	Mean Event PM Peak Travel Rate	Number of Deviant Intervals
125+04979	Lake Boone Trail	1.3196	1.0558	0
125P04979	Lake Boone Trail	0.4010	1.0948	2
125+04980	Wade Ave Ext.	0.3720	1.1308	2
125P04980	Wade Ave Ext.	0.5257	1.1830	4
125+04981	Hillsborough St. (NC 54)	0.1090	1.1634	6
125P04981	Hillsborough St. (NC 54)	0.1841	1.1353	6
125+04982	Western Blvd.	0.6689	1.0706	4
125P04982	Western Blvd.	0.4780	1.1035	7
125+04983	Melbourne Rd.	0.1367	1.0829	3
125P04983	Melbourne Rd.	0.2978	1.0276	0
125+04984	Jones Franklin Rd.	0.6390	1.0023	0
125P04984	Jones Franklin Rd.	0.1634	1.0038	0
125+04985	I-40/US 1/US 64	0.2198	0.9804	0
TOTALS:		**5.5149**		**34**

Exhibit I-B - 36 shows CDF plots for 125+04980 and 125+04984 for both event data during the PM peak period and PM peak periods over the entire study year. Unlike previous facility directions, the facility distributions had higher 95th percentile travel rates than the event distributions. The facility buffer time for 125+04980 was 2.2813 compared to the event buffer time index of 0.8103. For 125+04984, the facility buffer time was 0.1765 compared to the event buffer time index of 0.0891.

I-440 EB and I-40 EB showed the largest impact, at least qualitatively, attributed to the special event. The rarity required to be designated a special demand-generating event means that reliability should not necessarily be expected during such events. Therefore, analysis of these abnormal events primarily identifies time/space observations that should be classified as abnormal rather than normal.

Exhibit I-B - 36: CDF plots for selected I-440 WB TMCs based on event travel rates or all PM peak periods



APPENDIX I – C: – SPATIAL ANALYSIS OF INCIDENTS

Unlike more traditional methods of crash analysis that focus on the vehicles involved and reconstructing a narrative, travel time reliability focuses on the impacts to other vehicles in the traffic stream. While priority is rightly placed on the safety of users and responding emergency personnel, incidents can significantly impair traffic operating conditions and are a major contributor to travel time unreliability. Incident locations logged in databases such as TIMS focus on correctly identifying the spatial location of the event rather than the spatial area in which users experience the impact of the collision. At the most basic level, operators in traffic control centers decide which dynamic message signs are to be updated with incident information, in part based on the deemed severity and likelihood of causing significant delay to upstream vehicles. These operators also decide how long the warning message should be displayed.

Travel time reliability monitoring systems are only as accurate as the input data used to construct distributions and models. Therefore, the more accurate the data on incident location and extent of impact relative to the impact experienced by users, the more accurate the reliability analysis will be. The NCDOT reliability monitoring system case study was developed using ex post facto data and analysis. Therefore, only data previously recorded were available for use. Operational reliability monitoring systems can benefit from observational data such as the effective spatial and temporal bounds of incidents. The use of remote video monitoring allows operators to visually determine incident impact extents and serves as a complement to automated qualitative monitoring systems that capture data for facilities not covered by a live traffic monitoring center or during hours a center to not staffed.

Direct observation can be very effective. However, more quantitative analysis methods may be needed to both account for possible variation between traffic control operators and provide greater coverage. To measure the effective incident extents of incidents, incident data reported along I-40 EB were used to develop a method based the number of deviant time-space observations before and after the incident. Travel rate time/period observations were originally deemed normal/abnormal based on the presence of external events. For incidents, the spatial and temporal extents described in the incident report were used to assign incident flags to time/space observations included in the spatiotemporal area defined by TIMS. Time/space observations lacking any event flags were deemed to be normal. Mean and standard deviation were tabulated for each TMC over each temporal analysis period. Normal travel observations were deemed deviant if they were outside of two standard deviations from the mean. These time/space intervals require additional analysis to determine the cause and why they weren't captured. If a monitoring system does not include flow rate data, deviant observations may reflect periods of recurring congestion. Even under ideal data collecting conditions, some data error and loss is to be expected, therefore, some deviant observations will be present.

Additional incident extent analysis started by identifying study periods adjacent both spatially and temporal from the beginning time/space region of each accident. Regions located within the bounds reported in TIMS are already flagged as abnormal, therefore, the focus was placed on adjacent time/space regions that may not have been included in the ranges provided by RITIS. From the starting temporal and spatial bounds, the previous 10 segments and 20 temporal intervals were set as the pre-incident study area to determine the average number of deviant observations spatially for each temporal interval and temporal for each spatial interval. To evaluate incident extents upstream of the incident location and the duration of impacts after the incident clears, the twenty temporal intervals beyond the reported end of the incident and the ten segments upstream of the spatial incident terminus. The number of deviant observations were tabulated for each incident and time/space combination in the control and study regions. The number of deviant cells were compared to the time and space averages to identify higher than normal regions indicative of influence from an adjacent incident. Table I-C - 1 shows spatial and temporal averages of the pre-incident study area, the number of deviant observations adjacent to incidents for each of the 200 time/space regions in the post-incident study area, and the difference between pre-incident average and each time/space region.

Table I-C - 1: Spatial analysis of incidents and development of incident extent study area

						Segments						
		10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	
		17	17	16	16	18	23	27	31	41	50	**Pre-Incident Average**
		-1.4	0.1	0.2	2.9	8.7	4.8	3.7	2.7	1.4	-11.0	Δ
Δ	**Pre-Incident Average**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	
53.4	14.7	36	34	33	40	52	71	97	122	120	76	**1**
49.7	14.1	35	38	37	42	55	73	88	106	102	62	**2**
42.0	15.3	34	40	39	45	53	70	82	89	69	52	**3**
39.5	16.4	36	41	38	46	55	69	75	76	69	54	**4**
33.9	17.8	38	39	36	46	50	62	58	66	65	57	**5**
28.4	19.1	34	36	37	37	41	51	53	63	65	58	**6**
26.2	20.2	33	35	30	35	39	51	55	63	65	58	**7**
19.7	21.8	27	29	26	34	35	45	48	55	61	55	**8**
20.4	20.8	24	23	25	32	41	49	50	54	57	57	**9**
13.3	23.6	24	24	21	26	36	44	44	49	51	50	**10**
12.5	23.1	21	25	25	26	33	40	43	47	50	46	**11**
10.6	26.8	23	27	30	28	32	41	44	48	52	49	**12**
8.9	26.9	22	25	29	30	31	38	41	47	48	47	**13**
6.3	26.1	21	22	23	27	29	32	36	44	44	46	**14**
1.3	27.3	18	19	17	20	25	29	32	38	44	44	**15**
1.9	25.0	16	17	16	19	27	28	31	34	42	39	**16**
1.3	24.8	16	17	18	23	29	25	27	31	39	36	**17**
-2.4	27.0	16	18	18	24	27	27	26	30	30	30	**18**
-9.6	31.7	14	17	17	22	27	26	22	25	26	25	**19**
-17.6	37.9	12	17	16	21	22	22	24	19	25	25	**20**

Excel Solver tool was used to determine the appropriate temporal and spatial extents such that the difference between the number of deviant observations at each extent and the pre-incident temporal and spatial average. Excel Solver was used to optimize the number of temporal and spatial intervals such that the sum of the deltas is as close to zero as possible. The optimized analysis space was the 10 preceding spatial segments and 16 subsequent temporal intervals. The analyst could either incorporate the entire time/space area or only those observations within the area that were calculated as deviant.