



University Transportation Research Center - Region 2

Final Report



**Performance Measures To Characterize
Directional Corridor Travel Time Delay
Based On Probe Vehicle Data**

Performing Organization: The College of New Jersey



January 2016



Sponsor:
University Transportation Research Center - Region 2

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The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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Project No(s):

UTRC/RF Grant No: 49997-18-25

Project Date: October 2015

Project Title: Performance Measures To Characterize Directional Corridor Travel Time Delay Based On Probe Vehicle Data

Project's Website:

<http://www.utrc2.org/research/projects/highway-corridor-length>

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| | | | |
|---|---|---|-----------|
| 1. Report No. UTRC: 49997-18-25 | 2. Government Accession No. | 3. Recipient's Catalog No. | |
| 4. Title and Subtitle PERFORMANCE MEASURES TO CHARACTERIZE DIRECTIONAL CORRIDOR TRAVEL TIME DELAY BASED ON PROBE VEHICLE DATA | | 5. Report Date January 2016 | |
| 7. Author(s) Thomas M. Brennan Jr. P.E, Ph.D. | | 6. Performing Organization Code | |
| 9. Performing Organization Name and Address The College of New Jersey 2000 Pennington Road Ewing, NJ 08628 | | 8. Performing Organization Report No. 10. Work Unit No. 11. Contract or Grant No. 49997-18-25 | |
| 12. Sponsoring Agency Name and Address University Transportation Research Center Marshak Hall - Science Building, Suite 910 The City College of New York 138th Street & Convent Avenue ,New York, NY 10031 | | 13. Type of Report and Period Covered final, Jan. 1, 2014 -June 30, 2015 14. Sponsoring Agency Code | |
| 15. Supplementary Notes | | | |
| 16. Abstract <p>Anonymous probe vehicle data are currently being collected on roadways throughout the United States. These data are being incorporated into local and statewide mobility reports to measure the performance of freeways and arterial systems. Predefined spatially located segments, known as Traffic Message Channels (TMCs), are spatially and temporally joined with probe vehicle speed data. Through the analysis these data, transportation agencies have been developing agency wide travel time performance measures. One widely accepted performance measure is travel time reliability, which is calculated along a series of TMCs. Travel time reliability is usually measured as a percentile of base travel time or speed. When reliable travel times are not achieved because of incidents and recurring congestion, it is desirable to understand the time and location of these occurrences to proactively manage the corridor.</p> <p>This research emphasizes a visually intuitive methodology that aggregates a series of TMC segments based on a cursory review of congestion hot spots within a corridor. Instead of a fixed congestion speed threshold, each TMC link is assigned a congestion threshold based on the 70th percentile of the 15-minute average speeds between 2AM and 6AM. An analysis of approximately 90-million speed records collected in 2013 along I-80 in northern New Jersey was performed for this project. Travel Time Inflation, the time exceeding the expected travel time at 70% of measured free flow speed, was used to evaluate each of the 166 directional TMC segments along 70 miles of I-80. This performance measure accounts for speed variability caused by roadway geometry, heavy traffic flows, and other Highway Capacity Manual speed-reducing friction-factors associated with each TMC.</p> <p>A t-stat analysis based on unequal means was conducted to compare each of the TMC segments to determine statistical similarities of adjacent TMCs. An example analysis of 5 Million records in 2013 during the AM Peak eastbound direction of I-80 in northern New Jersey was performed for this research. The results determined that of the 83 segments in the eastbound direction there were 25 statistically similar groups.</p> | | | |
| 17. Key Words Probe Vehicles, Travel Time Analysis, Data Collection | | 18. Distribution Statement | |
| 19. Security Classif. (of this report) Unclassified | 20. Security Classif. (of this page) Unclassified | 21. No of Pages 34 | 22. Price |

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ACKNOWLEDGMENTS

The authors would like to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) Foundation - Ministry of Education of Brazil for providing funding for our undergraduate researchers. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the sponsoring organizations. These contents do not constitute a standard, specification, or regulation. This research is being funded by the Region 2- University Transportation Research Center (UTRC). The speed data and segment information used in this report was obtained from INRIX Inc.

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ABSTRACT

Anonymous probe vehicle data are currently being collected on roadways throughout the United States. These data are being incorporated into local and statewide mobility reports to measure the performance of freeways and arterial systems. Predefined spatially located segments, known as Traffic Message Channels (TMCs), are spatially and temporally joined with probe vehicle speed data. Through the analysis of these data, transportation agencies have been developing agency wide travel time performance measures. One widely accepted performance measure is travel time reliability, which is calculated along a series of TMCs. Travel time reliability is usually measured as a percentile of base travel time or speed. When reliable travel times are not achieved because of incidents and recurring congestion, it is desirable to understand the time and location of these occurrences to proactively manage the corridor.

This research emphasizes a visually intuitive methodology that aggregates a series of TMC segments based on a cursory review of congestion hot spots within a corridor. Instead of a fixed congestion speed threshold, each TMC link is assigned a congestion threshold based on the 70th percentile of the 15-minute average speeds between 2AM and 6AM. An analysis of approximately 90-million speed records collected in 2013 along I-80 in northern New Jersey was performed for this project. Travel Time Inflation, the time exceeding the expected travel time at 70% of measured free flow speed, was used to evaluate each of the 166 directional TMC segments along 70 miles of I-80. This performance measure accounts for speed variability caused by roadway geometry, heavy traffic flows, and other Highway Capacity Manual speed-reducing friction-factors associated with each TMC.

A t-stat analysis based on unequal means was conducted to compare each of the TMC segments to determine statistical similarities of adjacent TMCs. An example analysis of 5 Million records in 2013 during the AM Peak eastbound direction of I-80 in northern New Jersey was performed for this research. The results determined that of the 83 segments in the eastbound direction there were 25 statistically similar groups.

EXECUTIVE SUMMARY

A complete paper can be found in the Transportation Research Record (1) and the compendium of papers for the ITS World Congress in Bordeaux (2). Based on the research, it is concluded that the uses of a variable free flow travel time evaluated on a fixed length highway segment, or Traffic Message Change (TMC), using anonymous probe vehicle data provides a means to account for variability in driver free flow speed caused by exterior factors as indicated by the Highway Capacity Manual (e.g. lane widths, shoulder width, etc...). For this research, the proposed 70% of the base free flow speed accounts for some of the free flow speed reduction friction factors identified by the highway capacity manual (HCM) along a TMC link. This percentage can be adjusted, but the 70% values has been used in previous research and is a good indication when congestion condition occur. Although a comprehensive view of the actual infrastructure was not conducted, it is a reasonable expectation that the geometric layout and other contributing factors associated with a highway segment will impact a TMC's base free flow speed, and ultimately the point when a TMC is considered to be congested. This new performance measure is graphically presented over a long period of time with intuitive two-dimensional and three-dimensional graphical representation of the travel times obtained from anonymous probe vehicle data. Additional findings indicated that fixed highway segments could be grouped based on similar travel times using a T-Test of adjacent segments. The results showed that out of 83 fixed highway segments, 25 groups or corridors, could be identified.

INTRODUCTION AND BACKGROUND

The development of travel time reliability performance measures using probe vehicle data is being addressed across the country to satisfy the performance-based portions of the Moving Ahead for Progress in the 21st Century Act (MAP-21). MAP-21 (3) is a 2-year \$105 billion surface transportation bill initiative that has provisions for better data collection of highway performance monitoring, continuous travel monitoring, and analysis. Probe vehicle speeds and location data provide a means to monitor and proactively manage highway systems. Each system experiences a variable number of conditions including weather, crash incidents, geometry layout, and construction. These data are also being used to identify areas of the nation's roadway infrastructure in need of improvement. Currently, the United States (US) holds a grade of 'D' by the American Society of Civil Engineering (ASCE) for roads (4), meaning that a large number of US roadways that remain congested. With a better understanding of the location, frequency, type of roadway congestion occurrences, and travel time reliability over a defined corridor a better capital improvement management plans can be developed.

There have been a number of reports developed in recent years using anonymous probe vehicle data. The Texas A&M Transportation Institute applied this type of data for their analysis in their national mobility reports that focused on city and urban centers for their Urban Mobility Reports (5, 6). Indiana has developed performance measures to rank interstate freeways on a statewide level, including commuter corridors (7, 8, 9) using different performance methods. Other agencies have also begun to use this data in their annual reports (10, 11, 12, 13). As probe vehicle data and other types of crowd data sources become more reliable, it is expected that performance measures developed from this data will also become more relevant. Before 2010, probe vehicle data was presented in 5-minute increments and it did not cover all major interstates and highways. However, since 2010 the fidelity of probe vehicle data has improved greatly and now includes both public and private crowd sources (8).

Congestion is defined in a number of research publications that include a binary measure of congestion hours, congestion index, and weighted congestion hours (14). These performance measures

work well, but they do not account of speed variation across the system due to changes in posted speed limits, geometric layout and roadway conditions. They instead rely on a fixed congestion threshold. Other indices that account for travel time or travel time deficiency (9) provide an additional means to measure travel time reliability, but remain associated with a fixed congestion speed threshold. The research presented builds upon previously defined congestion performance measures (14, 15) which are based on fixed speed threshold by proposing highway congestion performance measures that account for speed variability between Traffic Message Channels (TMCs). The research concludes by presenting an improved visualization for highway segment, and corridor performance which is currently in press with the Transportation Research Record (1). In addition, this research proposes a quantitative grouping of statically similar highway segments into defined travel corridors to better evaluate travel time reliability under similar congestion conditions.

DATA

New Jersey's Interstate 80 is a 70 mile highway located across the northern part of New Jersey connecting Pennsylvania to New York, NY. A diagram of the corridor is shown in Figure 1. I-80 traverses both rural and urban areas, has varying speed limits, and has varying geometric layouts both vertically and horizontally. Its proximity to New York City, one of the largest cities in the world, creates a complex corridor with an AADT of around 122,000 and a number of major intersections with freeways. The complexity of the corridor makes evaluating its performance difficult. The study corridor is comprised of 166 TMC segments that are associated with minute by minute anonymous probe vehicle speed data. Each TMC is defined by its spatial attributes as well as its corresponding interstate name, which is stored in a database table. An example of these attributes is shown in Table 1. For the 166 TMCs analyzed, there were approximately 90 million 1-minute speed records analyzed for the corridor. An example of the speed records stored in a database are shown in

Table 2. For this research only data points with a confidence score of 30 were used. This score indicates that a speed measure was obtained directly from probe vehicles, as opposed to a score of 10 or 20, which would indicate the speed value was calculated based in part on historic data. Each speed associated with a TMC was then aggregated into 15-minute space mean speed (SMS) bins, 96 total, over a 24 hour period for each day in 2013 and subsequently stored in a new database table. The 15-minute speeds associated with each TMC for each day of the year are subsequently used to develop the traffic performance measure and visualization methods proposed in this report. The use of SMS instead of average speed provides a more conservative estimate that accounts for the variability in vehicle speed as it traverses a TMC.

To assess a series of TMCs as a defined corridor with similar speed patterns, the 15-minute speeds associated with each TMC for each day of the year are subsequently used to develop a method to group subsections of highway segments that experience similar congestion conditions (2). The use of SMS accounts for the variability in vehicle speed as it traverses a TMC, while the aggregation method will account for similar congestion conditions on adjacent segments.

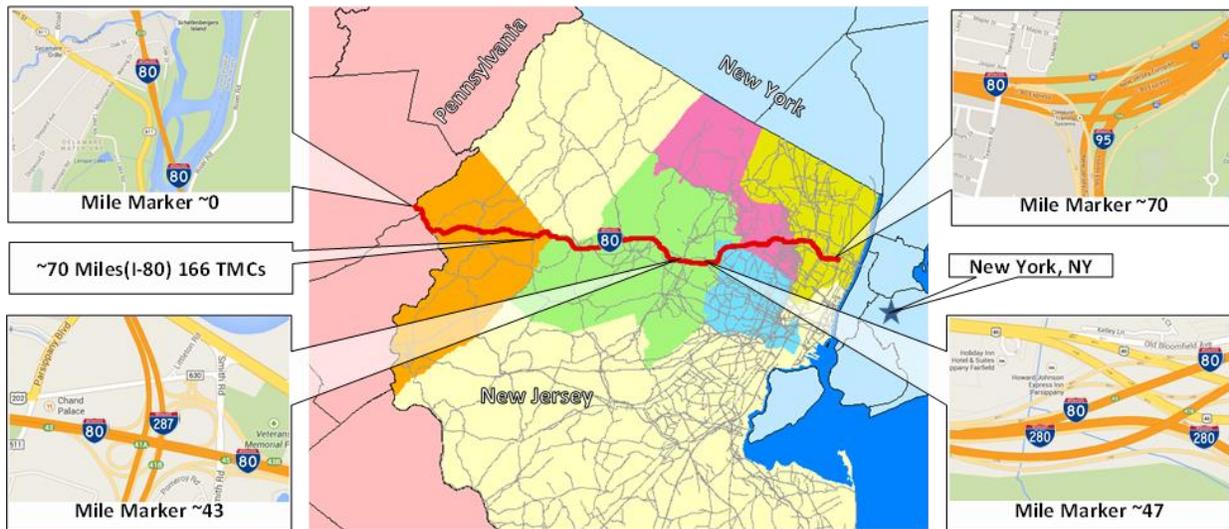


Figure 1. I-80 Corridor in northern New Jersey.

Table 1. Example of Traffic Message Channel (TMC) network spatial attributes

| TMC | Road/ Direction | Length (Miles) | Lat. Start | Long. Start | Lat. End | Long. End |
|-----------|--------------------|-------------------|---------------|----------------|-------------|--------------|
| 103+05337 | I-080 W | 0.01535 | 39.0271 | -74.4507 | 39.0325 | -74.4674 |
| 103P05336 | I-080 W | 0.01338 | 39.0229 | -74.4439 | 39.0271 | -74.4507 |
| 103-05336 | I-080 E | 0.01338 | 39.0285 | -74.4546 | 39.0321 | -74.4546 |
| 103N0533 | I-080 E | 0.00415 | 39.0271 | -74.4507 | 39.0285 | -74.4546 |

Table 2. Example of 15-minute binned probe data with TMC speeds.

| TMC | Date Time Stamp | SMS (MPH) | Confidence Score |
|-----------|---------------------|-----------|------------------|
| 103+05337 | 2011-01-01 01:00:00 | 65 | 30 |
| 103+05337 | 2011-01-01 01:15:00 | 64 | 30 |
| 103P05336 | 2011-01-01 01:00:00 | 45 | 30 |
| 103P05336 | 2011-01-01 01:15:00 | 42 | 30 |

CONGESTION

Previous research has considered any TMC i to be congested during a period of time j when the calculated SMS v_{ij} falls below a pre-defined speed threshold v_e , typically 45 mph for highways (7, 8, 15). Using a fixed speed threshold does not account for variations in the road geometry, the number of ramps, changes in posted speed, or other highway capacity manual (HCM) speed-reducing friction factors that can contribute to reduction in speed. Therefore, presented in this research is a variable speed threshold used to compare against each calculated SMS (v_{ij}) over a 15-minute period. The variable speed threshold is calculated using the following:

$$v_{ia} = 0.70 \frac{1}{n_{ij}} \sum v_{ij} \quad 1$$

where v_{ia} is the variable speed threshold, n_{ij} is the total count of the 15-minute SMS bins between 0200 and 0600 hours for a full year. The SMS were calculated in the early morning hours when lower volumes are present and vehicles are expected to be traveling in free flow conditions. A similar approach, using a dynamic free flows speed based on the maximum average over a time period, was used to evaluate congested conditions in a report by the European Joint Research Commission (16). The variable v_{ia} is based on 70 percent of the average SMS for the defined time period. The 70 percent can

be adjusted based on an agency's need, but was chosen because previous studies used 45 MPH as the fixed speed threshold, which is approximately 70% of 65 MPH (7,8). Other reports have suggested threshold speeds around 35 mph in large urban areas and 55 mph in small urban areas (). A binary indicator (15) was used to calculate the number of times an observed SMS fell below the variable threshold value for a TMC as shown in the following:

$$\delta_{ij} = \begin{cases} 1, & v_{ij} < v_{ia} \\ 0, & v_{ij} \geq v_{ia} \end{cases} \quad 2$$

where v_{ia} is the variable congestion threshold speed for any TMC segment i during any 15-minute period j and δ_{ij} is a binary indicator that equates to '1' when the SMS falls below v_{ia} .

Congestion Hours

Aggregating the frequency when a TMC segment falls below the binary congestion threshold (v_{ia}) provides a simplistic calculation to quickly identify areas where congestion may be of concern. This aggregation has been defined in previous research (7, 8, 15) and is redefined in the following equation:

$$VCH_{G,T} = 0.25 \sum_{i \in G} \sum_{j \in T} \delta_{ij} \quad 3$$

where, VCH is the number of congestion hours based on a variable threshold speed, G represents the group of TMC segments and T represents time periods being considered. The 0.25 constant aggregates the 15-minute congestion periods into hours.

The fixed speed threshold (45mph) is compared to the variable speed threshold in Figure 2. Using the variable speed provides a less conservative, but more accurate indication of congestion because it accounts for speed variation between different TMCs. As shown in the figure, the use of the variable speed threshold shows less congestion for the aggregated monthly congestion hours along I-80, thus limiting the number of potential false congestion hour indications. The aggregation of each TMC's congestion is shown in Figure 3, which is adapted from previous research used to illustrate congestion hours along a corridor (7, 8). Each TMC is represented by its mile marker (MM) designations, which

provides the relative length of each TMC segment along the corridor. The major change from previous research is that for this graph the congestion speed threshold values vary for each TCM along the corridor. Most of the congestion in Figure 3 appears to be recurring with the exception of the westbound direction when higher values were observed in May, June, and July. The drawback with this type of graph is that it does not show the intensity of the congestion, the time of day when congestion is occurring and it does not account for the TMC length. The TMC length is important when comparing longer and shorter segments that may have the same number of congestion hours. A longer segment will inherently impact a greater number of drivers under equal volumes and lane numbers.

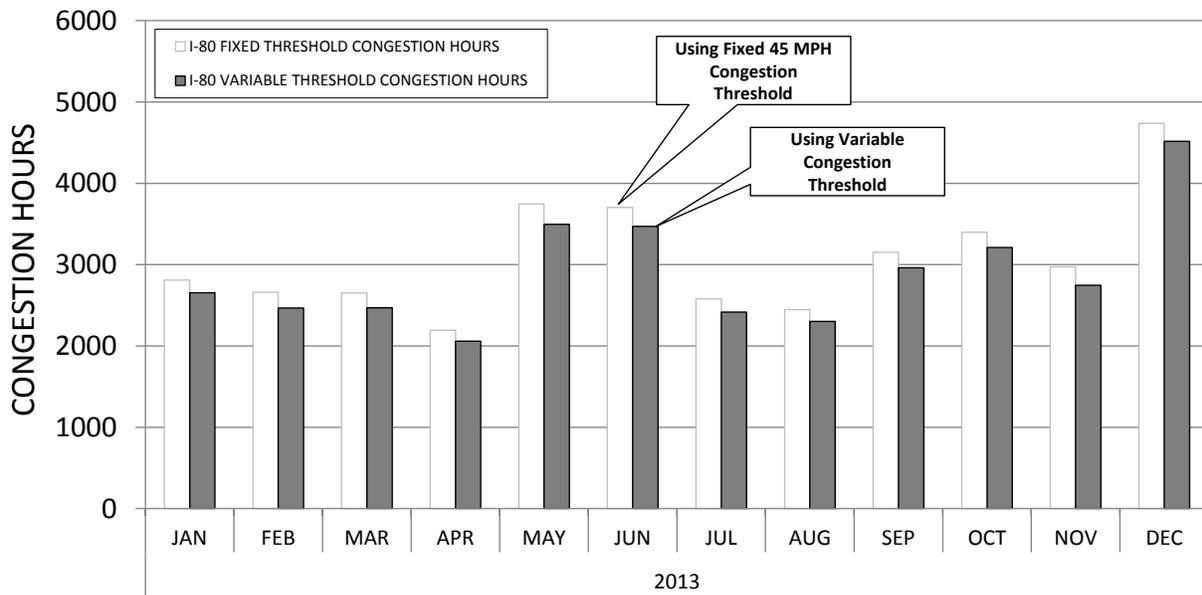


Figure 2. Aggregated directional congestion hours.

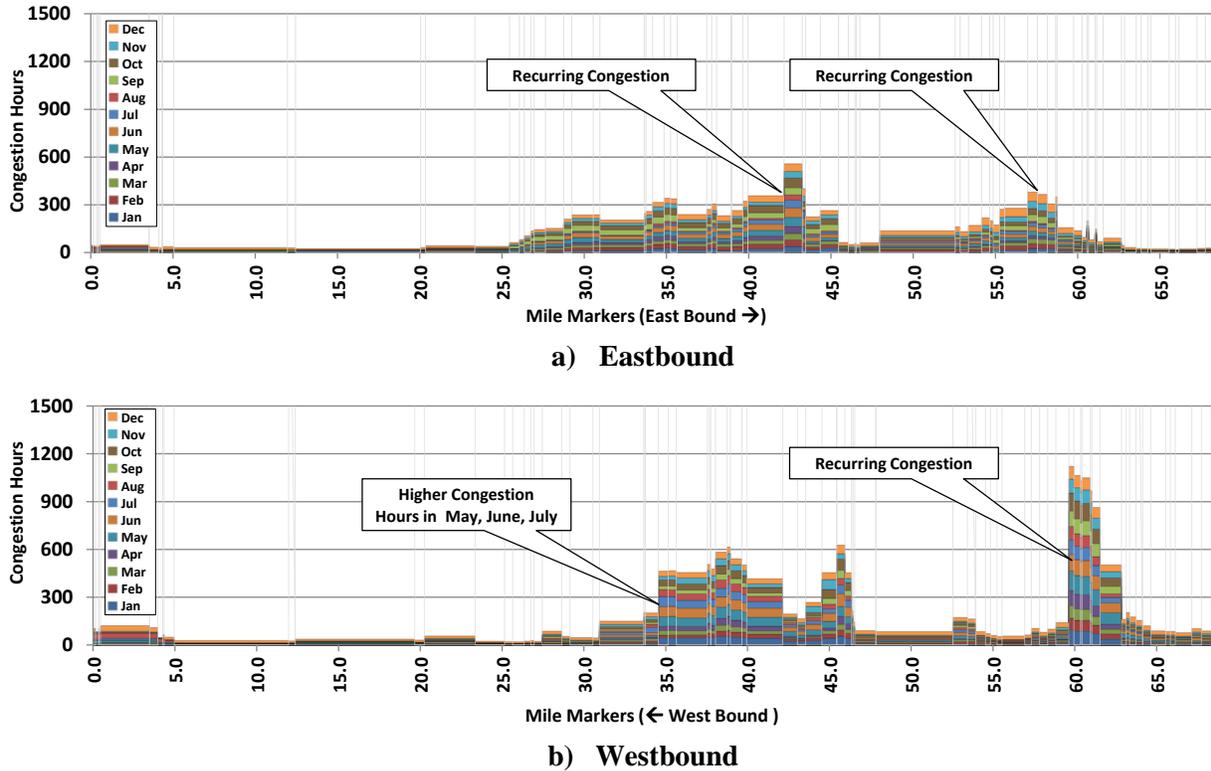


Figure 3. I-80 Congestion Hours below a variable congestion threshold speed in 2013.

Travel Time Inflation

The Travel Time Inflation (TI) performance measure was developed to take into account both the distance and speeds for each TMC. Similar to the variable speed congestion hours, each TMC is assigned a base travel time (BTT) that accounts for the TMC’s length and observed 70th percentile free flow speed. The base travel time for each TMC is a function of the variable threshold speed and is defined in the following:

$$BTT_i = \frac{x_i}{v_{ia}} \tag{4}$$

Where BTT_i is the base travel time in hours for TMC i and x_i is the distance in miles for the TMC. Any increase in travel time will occur when the binary indicator defined in Eq.2 (δ_{ij}) is equal to 1. The travel time for any TMC segment is defined as the following:

$$TT_{ij} = \begin{cases} \frac{x_i}{v_{ij}}, & v_{ij} < v_{ia} \\ 0, & v_{ij} \geq v_{ia} \end{cases} \quad 5$$

where TT_{ij} is travel time in hours of TMC i at time period j . The travel time is only calculated when the observed speed v_{ij} is less than the variable threshold speed v_{ia} . When v_{ij} is greater than the variable threshold speed v_{ia} , the level of congestion is considered to be above the threshold and therefore not counted resulting in $TT_{ij} = 0$. It is the summation of the difference between the actual travel time and the base travel time that is used to define TI, which is shown in the following:

$$TI_i = \sum_{j=1}^n (TT_{ij} - BTT_i) \quad 6$$

where TI_i is the total Travel Time Inflation for TMC segment i for all 15-minute bin time periods j within a time frame defined by the analyst. The TI performance measure takes into account the time it takes to traverse a segment. By aggregating the TI values over time, a representation of the relative congestion intensity can be evaluated. Using travel time inherently weights the distance when comparing different TMC segments. The results of this performance measure are shown in Figure 4. When compared to Figure 3, there are areas that may not have a high frequency of congestion, but indicate increased travel time. This can be observed in Figure 4a, where the eastbound TI is higher in December, which may be related to weather because both directions were affected (Figure 4b). Also in Figure 4, recurring congestion is observed between MM 55 - 60 in the eastbound directions and MM 63.7 - 60 in the westbound direction. For the eastbound direction (Figure 4a), as traffic approached the I-80 expressway into New York City, the TI values decreased. This indicates a reduction in travel time as vehicles depart local I-80 to enter the I-80 expressway (Figure 1). In the westbound direction (Figure 4b) the opposite effect occurs. The TI increased when the I-80 expressway ends, but decreased over the next 4 miles. In Figure 4 the I-80 congestion hotspots are identified by a pronounced increase in TI. It is expected that most of the TI occurs during the AM and PM peak travel times, but this information cannot be interpreted from the graph.

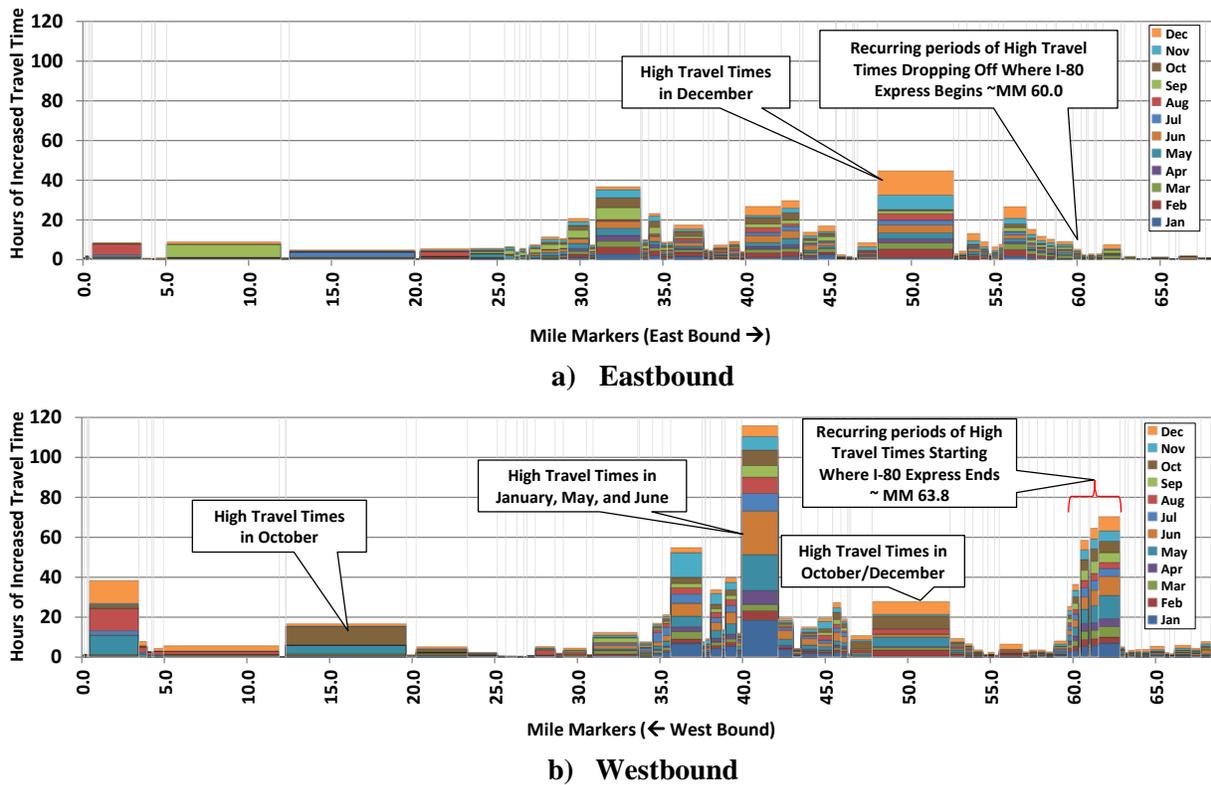


Figure 4. Total hours of Travel Time Inflation based on Variable Threshold Congestion Speed.

Corridor Travel Time Inflation

In Figure 4, the westbound direction has two areas of high congestion between MM 52.5 and 39.6. The two peak congestion points are located at MM 40 and MM 50. MM 40 experienced an atypical reduction in TI during January, May, and June. MM 50 experienced an increased TI during October and November. Between these two peaks there appears to be relatively little congestion. To better understand what is occurring on this 12.85 mile portion of westbound I-80, an aggregation of the TMC TIs between MM 52.5 - 39.6 is calculated. The Corridor Travel Time Inflation (CTI) equation is adapted from previous research (8, 9, 15) and defined in the following:

$$CTI_{(S,T)} = \sum_{i \in S} \sum_{j \in T} [\delta_{ij} (TT_{ij} - BTT_i)] * 60 \tag{7}$$

The *CTI*, shown in minutes, is the summation of all of the TIs within a series of TMC segments. The constant 60 in the equation converts the hours of CTI into minutes. Using this performance measure, a series of TMC segments *S* for time periods *T* can be characterized and graphed.

TRAVEL TIME INFLATION VISUALIZATION

The CTI defined in Eq. 7 was applied to the segments between MM 52.5 - 39.6 on westbound I-80 (Figure 4b). Figure 5 shows a single week (June 9 – 15) illustration of the crowd sourced data to identify the amount of CTI occurring along the corridor. The longer the TMC the more of an impact it will have on the CTI. A sample section of one week of data along westbound I-80 from MM 52.8 - 39.6 is shown in Figure 5. In the figure the number of CTI minutes are represented by the color contour bands (19). The callouts are defined as follows:

- Callout i: This line represents the 24-hour time period for the corridor. CTI will appear on this line and is effectively independent of other days.
- Callout ii: This line represents a transitional line from one day to the next. When CTI appears on this line it could indicate recurring congestion across the corridor. For this case, there is no recurring congestion at this time.
- Callout iii: This small amount of CTI over 5-minutes could represent an incident on June 11 between 1000 and 1345. There is CTI occurring during this time period but it is not observed on June 10 or June 12, meaning it is isolated to June 11.
- Callout iv: This shows the beginning of congestion starting around 1430 on a Friday afternoon. It is not uncommon to have heavier traffic heading east out of New York on a Friday evening (Figure 1).
- Callout v: The duration of the congested period started at 1430 and ended around 2015, peaking at 1715. It is noted that on June 15, a Saturday, no congestion delay is observed.
- Callout vi: recurring congestion is observed starting June 12 through June 15, with a three day peak occurring around 1730.
- Callout vii: On Jun 13 the congestion duration was less severe when compared to the 14th, while lasting longer with less intensity when compared to the 12th.

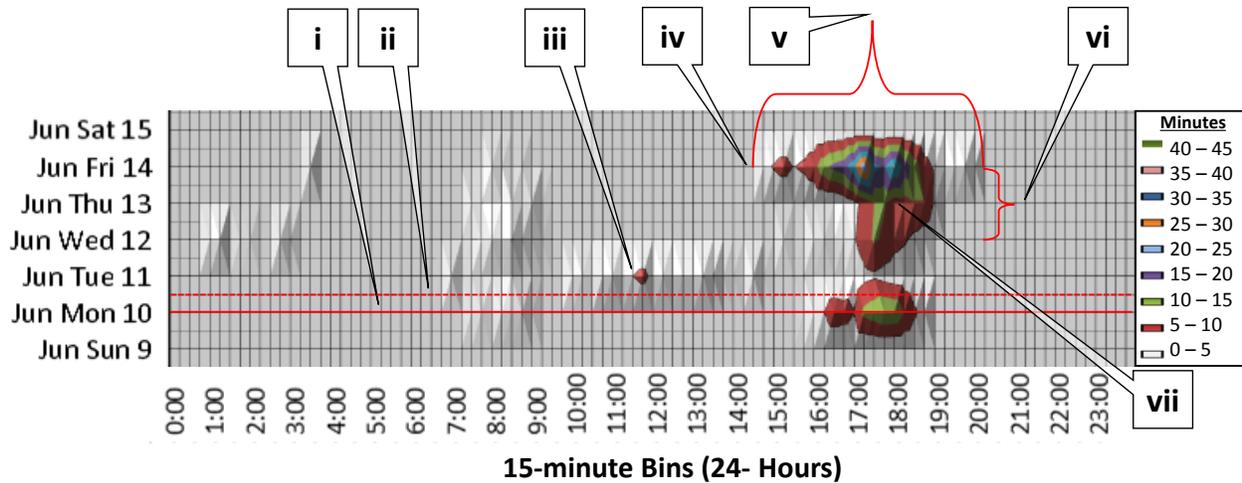


Figure 5. One-week example of 24-hour plots of Corridor Travel Time Inflation between westbound mile markers 52.5 – 39.6.

Visualizing the CTI data in this way allows a temporal representation of congestion. This allows trends to be seen over the course of a day or week and allows a viewer to understand if the congestion is recurring or non-recurring. Previously identified in Figure 4b was a high amount of TI during May and June in the westbound direction of I-80 ending near MM 40. By arranging a series of 1 week graphs, a two month illustration of the CTI is produced (Figure 6). In the figure the AM and PM peak times can be observed. Isolated incidents that are outside of the peak travel times, but influenced the overall congestion (Figure 4) can also be observed. The callouts in Figure 6 are defined as follows:

- Callout i: Small, recurring instances of the CTI appear in the AM Peak, heading westbound away from New York City.
- Callout ii: An isolated incident that lasted approximately 45 minutes appears to occur just before the AM peak.
- Callout iii: A more intense incident appears to have occurred in the middle of the AM Peak, lasting for 2.5 hours.
- Callout iv: A major incident lasting from 1000 to 1530 incurred corridor CTI in excess of 40 minutes above the normal threshold for congested travel time.
- Callout v: Recurring congestion is observed. Also noted is the decrease in CTI on the weekends during the PM Peak.

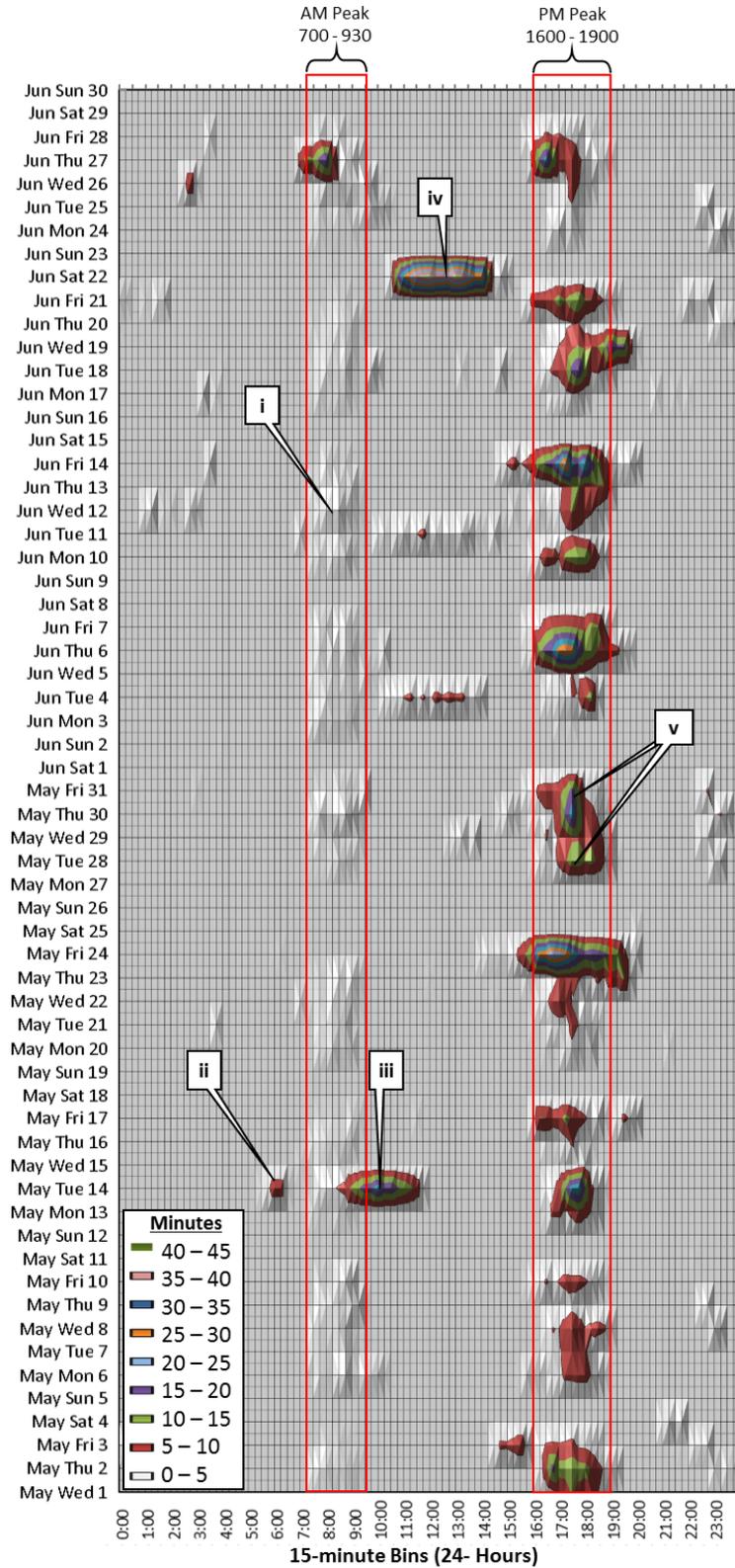


Figure 6. Plan layout of 24-hour plots of Corridor Travel Time Inflation for westbound mile markers 52.5 – 39.6.

The two incidents shown in Figure 6 (callouts iii & iv) were major contributors to the TI observed during May and June in Figure 4b. Viewing the data in series allows recurring congestion to be viewed with respect to outlier congestion that may adversely impact generalized congestion hour calculations. Another way to view this data is in an isometric view (Figure 7), where the two incidents (callouts i & iv) are easily identified. In addition, callout ii shows excessive congestion on the Friday before Memorial Day weekend, while callout iii shows an incident where the travel time varies every fifteen minutes. This variation in speed is affiliated with stop and go traffic. Viewing the data in this perspective provides another means to evaluate the system performance along corridor.

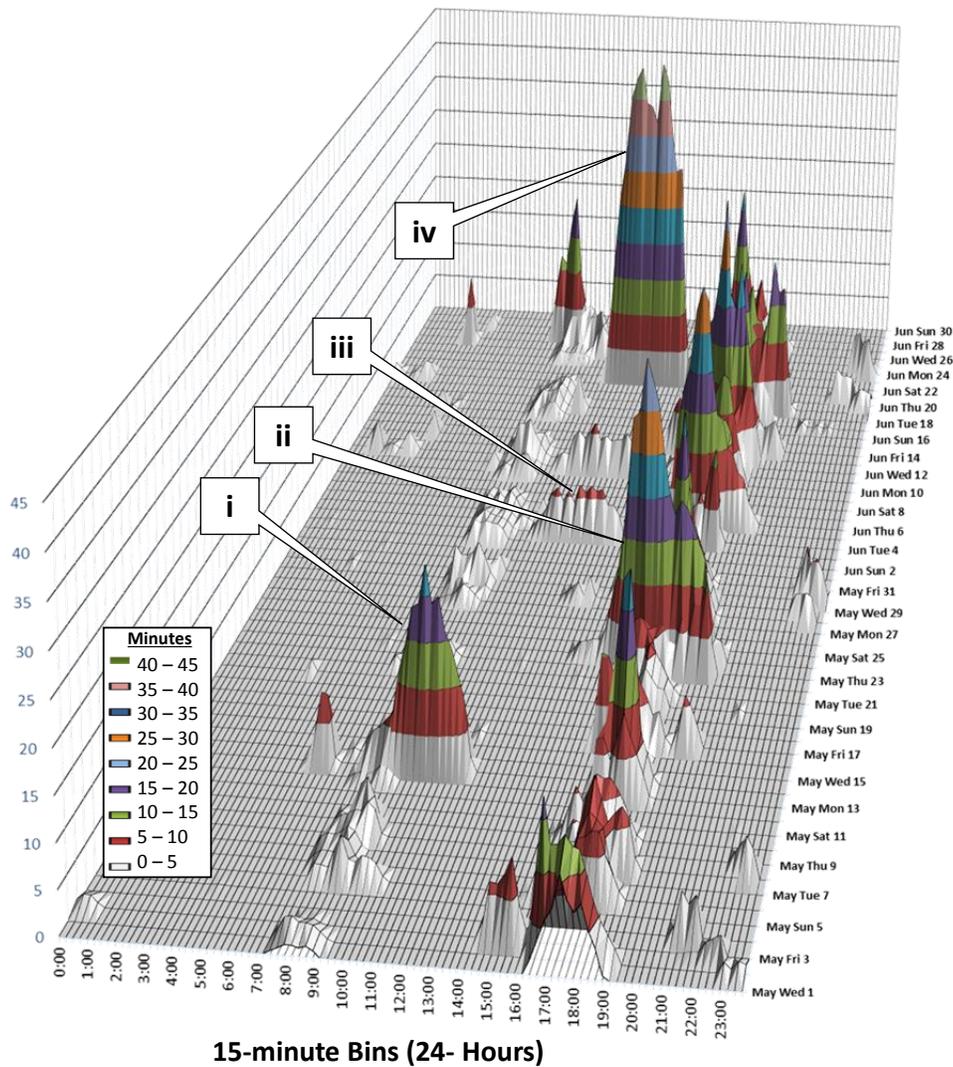


Figure 7. Isometric layout of 24-hour plots of Corridor Travel Time Inflation for westbound mile markers 52.5 – 39.6.

Assembling a series of 24-hour CTI graphs over a one year period provides a method to evaluate the travel corridor through multiple seasons. The results shown in Figure 8 indicated that the system appeared to be relatively consistent throughout the year, leading to the conclusion that the travel time of the corridor is reliable. This does not mean there is no congestion, instead it indicates that the expectation of a driver leaving New York City at 1630 are reliable for a majority of Fridays throughout the year. At the beginning of January (Figure 8), there appears to be an unusually high amount of congestion in the PM Peak period. Viewing the data in an isometric perspective relays a better understanding of the proportional increase of CTI during the beginning of January (Figure 9 callout i). In the same figure, callout ii shows a blizzard that occurred on February 8th (18) and callout iii shows an isolated incident that occurred at the beginning of the PM Peak in April. The individual impacts of each of the 14 TMC segments that make up the 52.5 to 39.6 westbound corridor during the February 8 storm are shown in Figure 10. From the figured it can be determined that the smaller the TMC segment, the less of an impact it has on the total CIT. Conversely, the longer the TMC segment the greater impact I can have on the CTI.

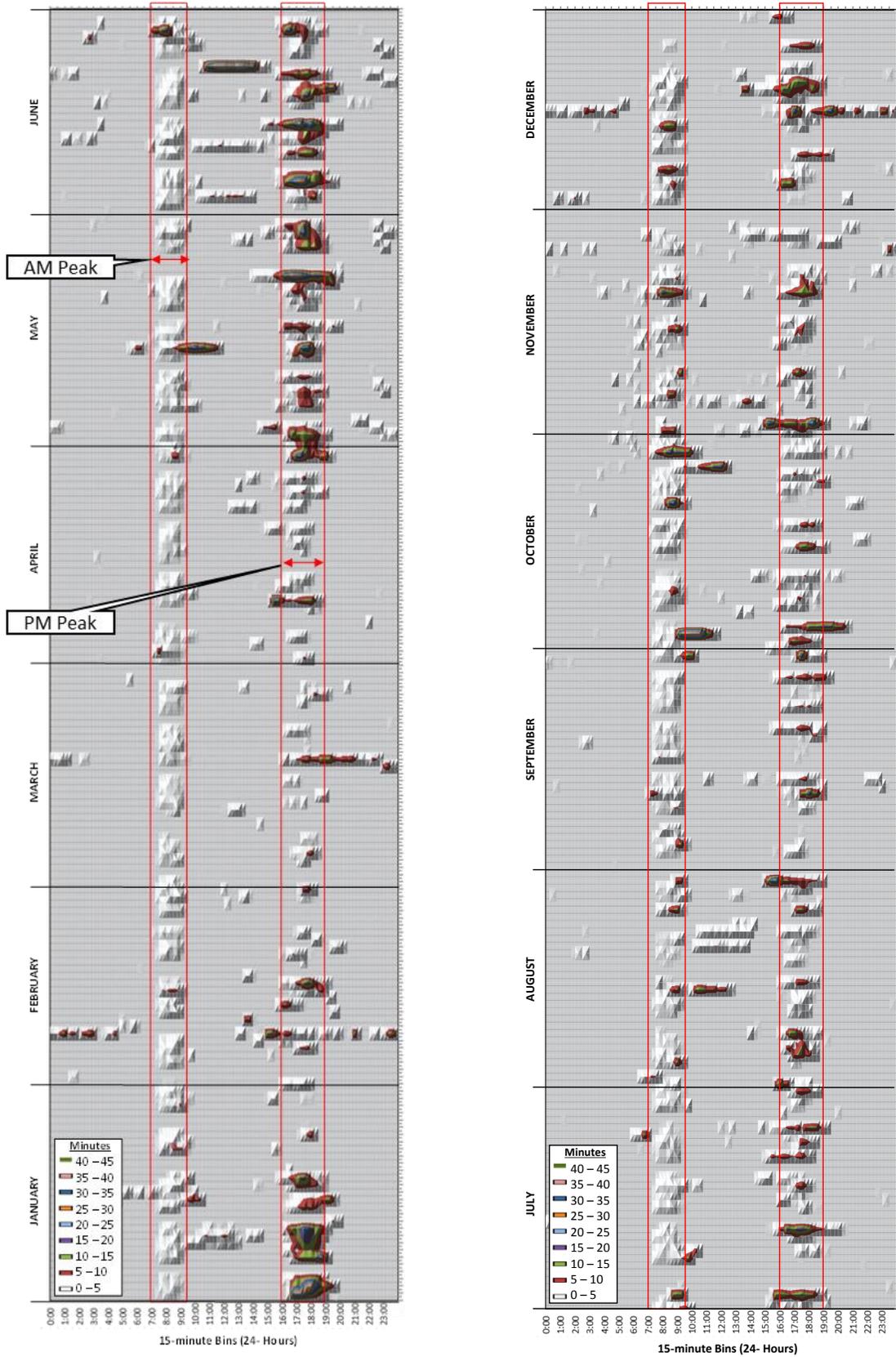


Figure 8. One year Corridor Travel Time Inflation for westbound mile markers 52.5 – 39.6.

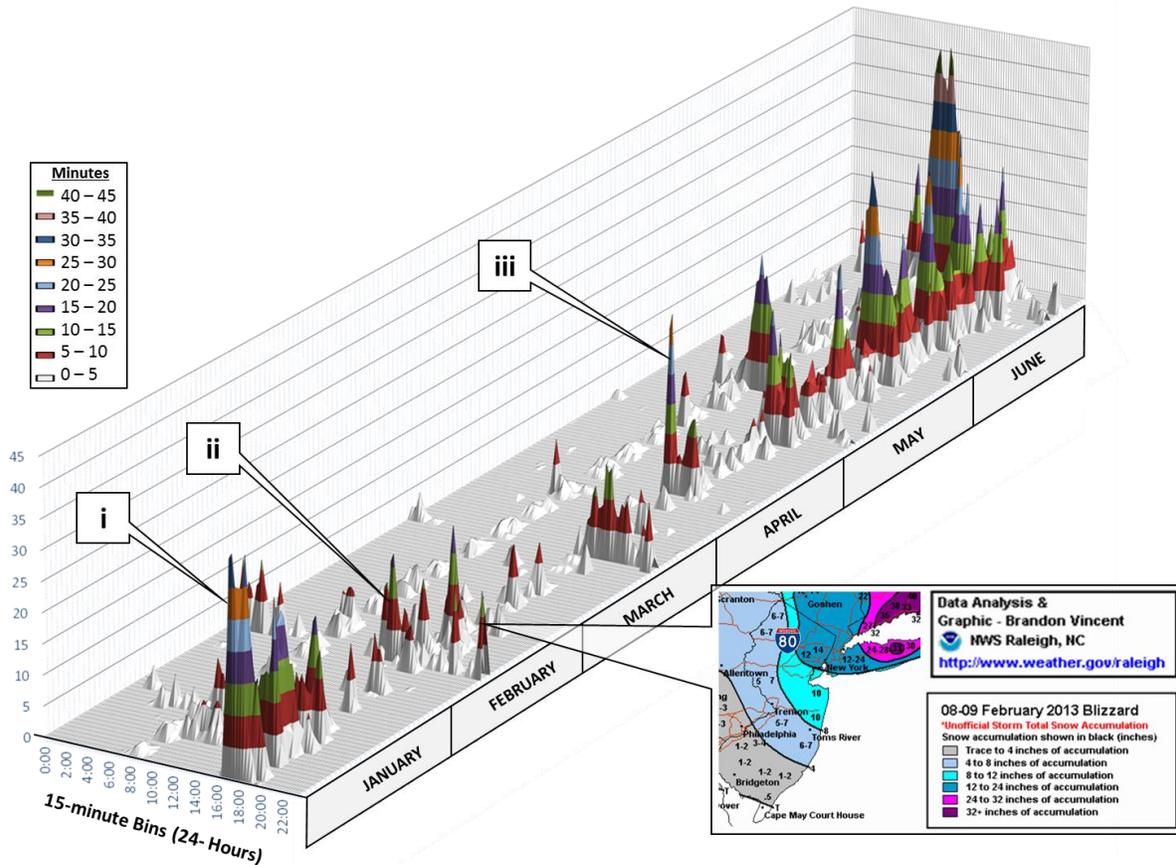


Figure 9. Isometric layout of 24-hour plots of Corridor Travel Time Inflation for westbound mile markers 52.5 – 39.6.

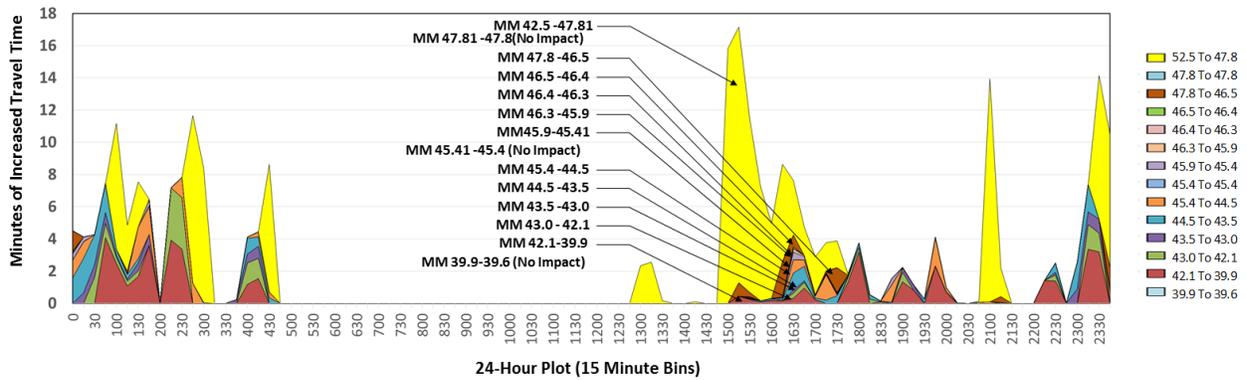


Figure 10. The contributing values of each of the 14 segments on the CTI values for the I-80 westbound corridor from MM 52.5 – 39.6 during the February 8, 2014 winter storm.

Incidents that impact both directions of traffic like weather, rubber necking, construction, and median crash incidents can be identified when both the eastbound and westbound direction CTIs are calculated and graphed. In Figure 11, a six month view of the CTI maps for both direction of I-80 are shown. The AM and PM peak times are labeled on the maps and are relatively consistent in each direction. Isolated traffic incidents are expected to appear in one direction and not the other, while weather events and major incidents are expected to impact both directions. On March 18th a late season winter storm (18) occurred (callout i) that impacted both directions of I-80. The major winter storm identified in Figure 9 (callout ii) appears in both directions of Figure 11 (callout ii). The use of the isometric CTI maps provide a definitive means to effectively relay the proportional increases in travel time incurred along a corridor. These types of illustrations provide a simplistic method to convey problem areas to an agency when making capital infrastructure investment decisions.

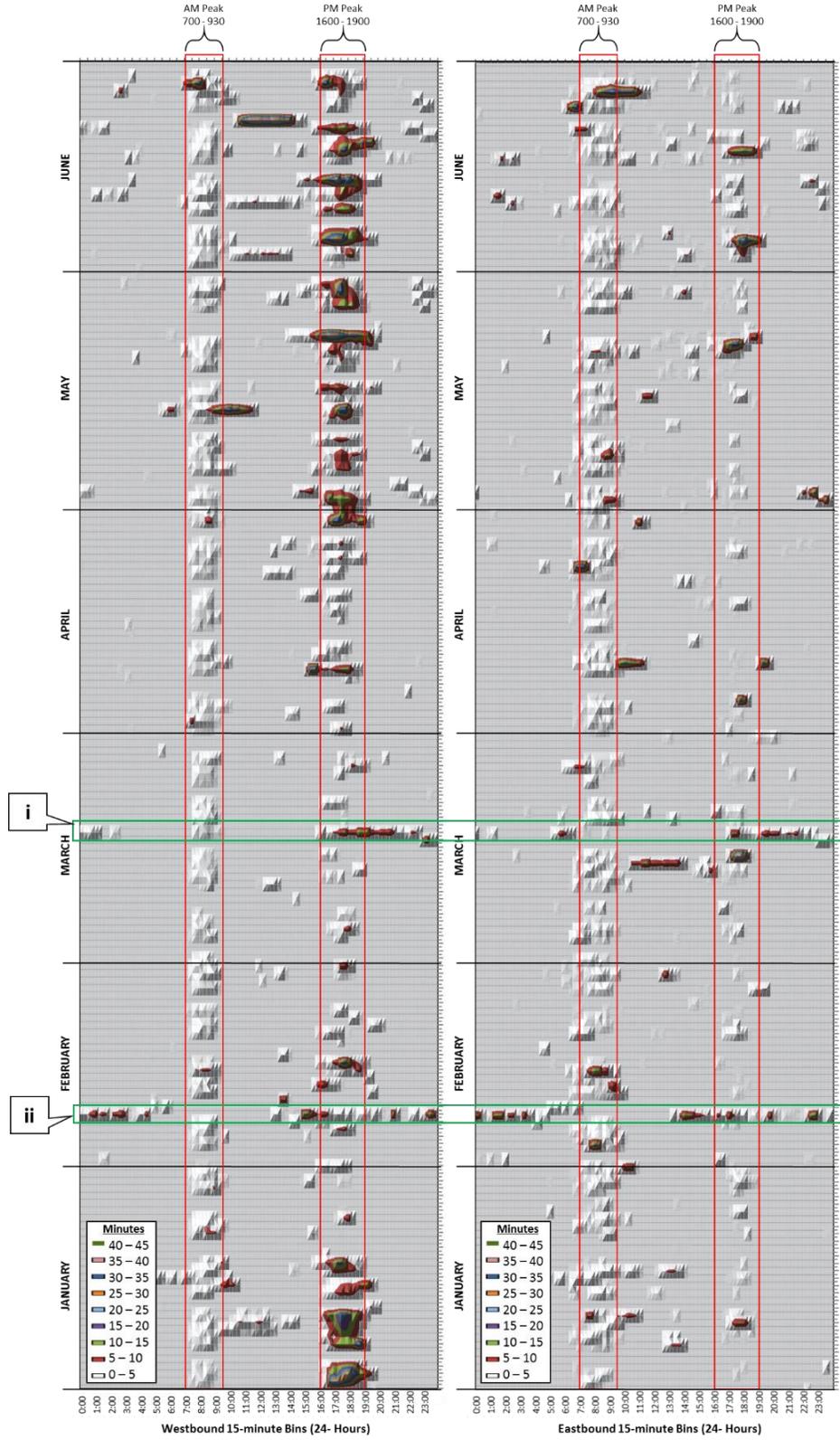


Figure 11. Side by side layout of Corridor Travel Time Inflation plot for eastbound and for westbound I-80 traffic between mile markers 52.5 – 39.6.

AGGREGATED SEGMENT TRAVEL TIME

By aggregating the TI values over time, a representation of the relative congestion intensity can be evaluated. The results of the travel time inflation performance measure are shown in Figure 4, where thicker bands indicate increased travel time. This can be observed in Figure 4a and Figure 4b where the eastbound TI is higher in December. For the eastbound direction (Figure 4a), as traffic approached the I-80 expressway into New York City, the TI values decreased. This indicates a reduction in travel time as vehicles depart local I-80 to enter the I-80 expressway (Figure 1). In the westbound direction (Figure 4b) the opposite effect occurs. The TI increased when the I-80 expressway ends, but decreased over the next 4 miles. In Figure 4 the I-80 congestion hotspots are identified by a pronounced increase in TI. It is expected that most of the TI occurs during the AM and PM peak travel times, but this information cannot be interpreted from the graph.

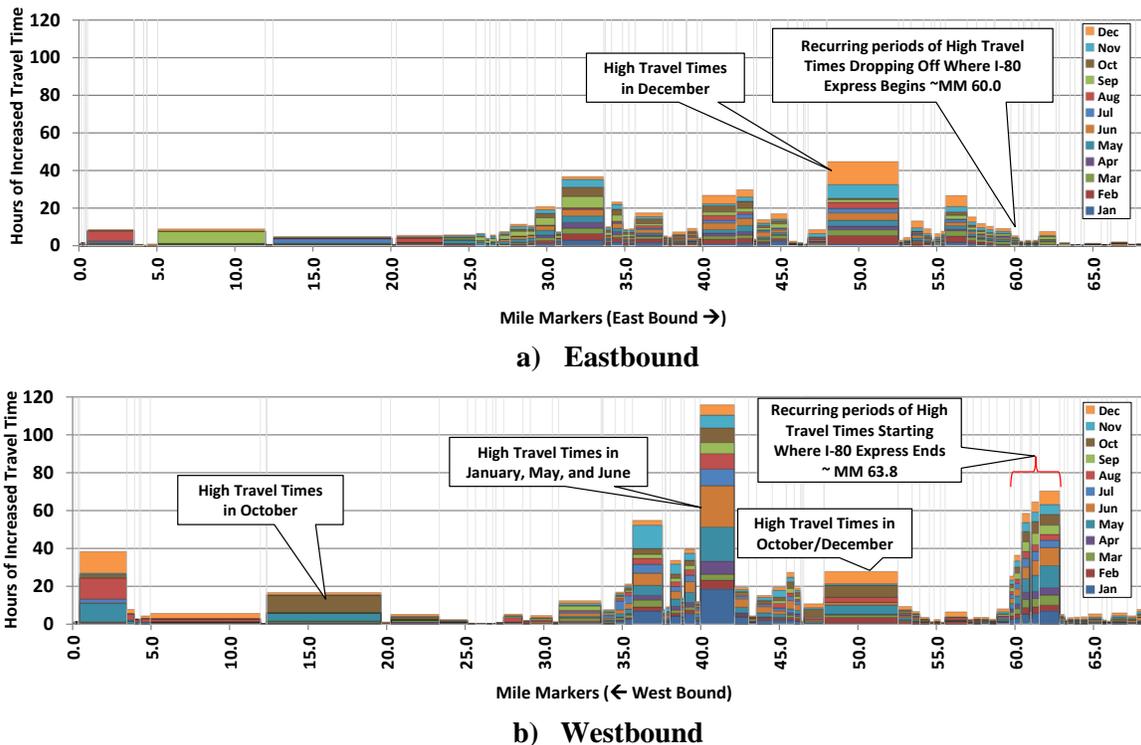


Figure 12. Total hours of Travel Time Inflation based on Variable Threshold Congestion Speed.

From Figure 4, it can be observed that the westbound direction has two areas of high congestion between MM 52.5 and 39.6. The two peak congestion points are located at MM 40 and MM 50. MM 40

experienced an atypical reduction in TI during January, May, and June. MM 50 experienced an increased TI during October and November. Between these two peaks there appears to be relatively little congestion, leading to the conclusion that the segments between the two mile markers can be grouped together to better understand what is occurring on this 12.85 mile portion of westbound I-80. An aggregation of the TMC TIs between MM 52.5 - 39.6 using the corridor travel time inflation (CTI) equation, defined in previous research (1):

Statistical evaluation of travel corridors

Although the approximate location of a change in increased travel times could be qualitatively observed in Figure 12, the appropriate groups of statistically similar segments cannot be determined directly from this graph. The problem with using just the TI as a performance measure is that it inherently reflects greater amounts of congestion for longer TMC segments. This makes it difficult to statistically compare the congestion characteristics of adjacent TMCs. Normalizing the increase in travel time with the Percent increases in Mean Travel time (PMTT) performance measure accounts for differences in TMC lengths. The PMTT is shown in the following equation:

$$PMTT_{ij} = \frac{TI_i}{BTT_i} \quad 8$$

where $PMTT_{ij}$ is the percent total Travel Time Inflation compared to the base travel time for a TMC segment i for a 15-minute bin time period j within a time frame defined by the analyst. A general representation of this performance measure is shown in Figure 13 where the relative increases in PMTT are plotted against the months of the year in 2013. Each mile marker (MM) is represented by a line with the top most line being the western most segment. With reference to the graph, segments with similarly spaced horizontal lines indicate a potential to consider these segments with similar congestion characteristics. The graph is plotted with respect to the months of the year to show the variation in this value during different types of seasons. A similar plot is shown in Figure 14, where each line represents a

month of the year plotted along the entire corridor. The PMTT during the AM Peak is shown in Figure 14a, while the aggregated increases are shown in Figure 14b.

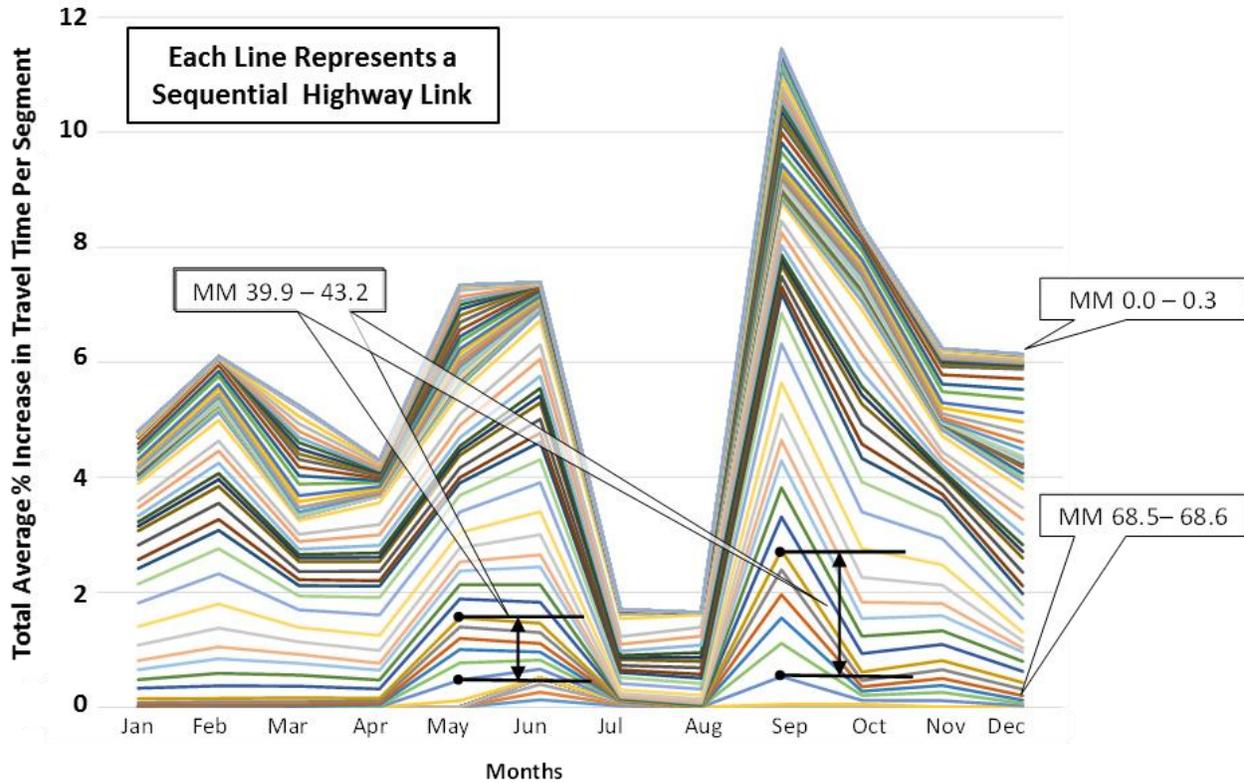
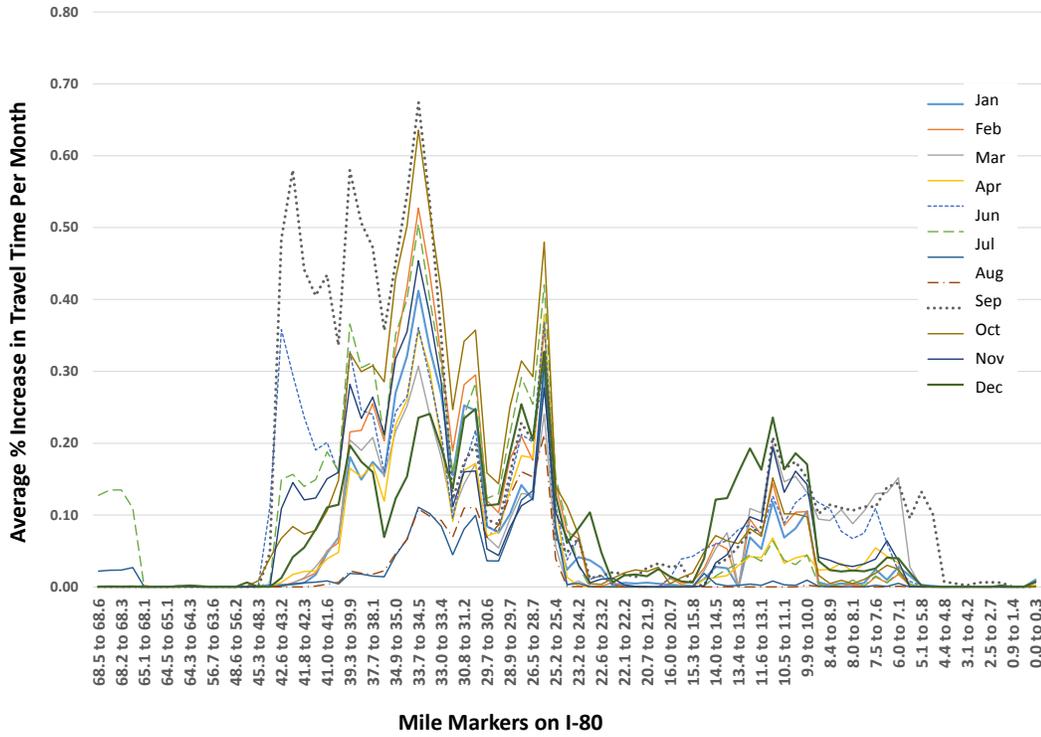
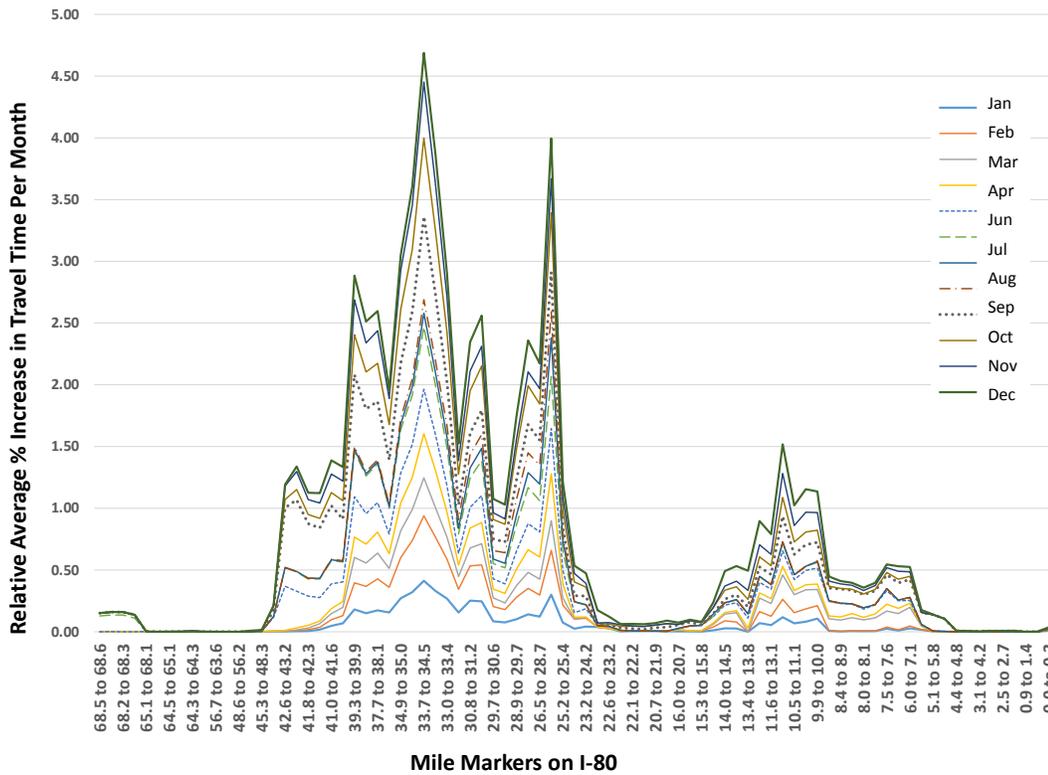


Figure 13. Relative differences between the mean values of the average percent increase in travel time per month.

An F-Test was performed on the background data to determine if the travel time mean values were near equal. From the F-Test it was determined that no highway segment had travel time means that were statistically similar. This result indicated that in order to perform a T-Test, an assumption that the mean values are unequal had to be made. The t-test was applied to each adjacent segment at a 99.9% confidence interval to minimize the number of groups. The results of the t-test with the respective p-values are shown in Table 3. The T-Test results indicate 25 distinct groups of I-80 which have travel time reliabilities in the eastbound direction during the AM Peak travel time period.



a. Average percent increase in Travel Time per Month



b. Aggregated average percent increase in Travel Time per Month

Figure 14. AM Peak eastbound differences between the mean values of the average percent increase in travel time I-80

Table 3. T-Test grouping of 83 eastbound AM Peak travel time highway segments along I-80, 2013

| Group | Mile Markers | P-Value for T-Test with Unequal Means | Boundary where Statistically Significant at 99.9% | Standard Deviation | Mean | Variance | Miles |
|--------------|--------------|---------------------------------------|---|--------------------|-------|----------|-------|
| 1 | 68.5 to 68.6 | 0.890 | | 0.237 | 0.012 | 0.056 | 0.11 |
| | 68.3 to 68.5 | 0.993 | | 0.245 | 0.013 | 0.060 | 0.22 |
| | 68.2 to 68.3 | 0.730 | | 0.244 | 0.013 | 0.059 | 0.09 |
| | 68.1 to 68.2 | 0.001 | Yes | 0.211 | 0.011 | 0.045 | 0.04 |
| 2 | 65.1 to 68.1 | 0.129 | | 0.007 | 0.000 | 0.000 | 3.00 |
| | 65.1 to 65.1 | 0.342 | | 0.001 | 0.000 | 0.000 | 0.06 |
| | 64.5 to 65.1 | 0.249 | | 0.002 | 0.000 | 0.000 | 0.58 |
| | 64.3 to 64.5 | 0.195 | | 0.010 | 0.000 | 0.000 | 0.19 |
| | 64.3 to 64.3 | 0.034 | | 0.014 | 0.001 | 0.000 | 0.03 |
| | 63.6 to 64.3 | 0.146 | | 0.004 | 0.000 | 0.000 | 0.69 |
| | 56.7 to 63.6 | 0.317 | | 0.000 | 0.000 | 0.000 | 6.92 |
| | 56.2 to 56.7 | 0.317 | | 0.002 | 0.000 | 0.000 | 0.48 |
| | 48.6 to 56.2 | 0.082 | | 0.000 | 0.000 | 0.000 | 7.60 |
| | 48.3 to 48.6 | 0.432 | | 0.024 | 0.001 | 0.001 | 0.28 |
| 45.3 to 48.3 | 0.000 | Yes | 0.031 | 0.001 | 0.001 | 3.01 | |
| 3 | 43.2 to 45.3 | 0.000 | Yes | 0.235 | 0.017 | 0.055 | 2.11 |
| 4 | 42.6 to 43.2 | 0.402 | | 0.646 | 0.097 | 0.417 | 0.57 |
| | 42.3 to 42.6 | 0.153 | | 0.618 | 0.109 | 0.382 | 0.30 |
| | 41.8 to 42.3 | 0.981 | | 0.475 | 0.092 | 0.226 | 0.46 |
| | 41.6 to 41.8 | 0.033 | | 0.439 | 0.091 | 0.192 | 0.20 |
| | 41.0 to 41.6 | 0.669 | | 0.477 | 0.113 | 0.228 | 0.64 |
| | 39.9 to 41.0 | 0.000 | Yes | 0.424 | 0.109 | 0.180 | 1.14 |
| 5 | 39.3 to 39.9 | 0.036 | | 0.732 | 0.235 | 0.535 | 0.52 |
| | 38.1 to 39.3 | 0.604 | | 0.572 | 0.204 | 0.328 | 1.22 |
| | 37.7 to 38.1 | 0.000 | Yes | 0.600 | 0.211 | 0.359 | 0.41 |
| 6 | 35.0 to 37.7 | 0.000 | Yes | 0.486 | 0.159 | 0.236 | 2.76 |
| 7 | 34.9 to 35.0 | 0.004 | | 0.667 | 0.248 | 0.445 | 0.03 |
| | 34.5 to 34.9 | 0.000 | Yes | 0.755 | 0.293 | 0.570 | 0.42 |
| 8 | 33.7 to 34.5 | 0.000 | Yes | 0.835 | 0.381 | 0.697 | 0.75 |
| 9 | 33.4 to 33.7 | 0.000 | Yes | 0.656 | 0.315 | 0.431 | 0.34 |
| 10 | 33.0 to 33.4 | 0.000 | Yes | 0.538 | 0.236 | 0.289 | 0.46 |
| 11 | 31.2 to 33.0 | 0.000 | Yes | 0.382 | 0.124 | 0.146 | 1.76 |
| 12 | 30.8 to 31.2 | 0.133 | | 0.551 | 0.191 | 0.304 | 0.35 |
| | 30.6 to 30.8 | 0.000 | Yes | 0.507 | 0.209 | 0.257 | 0.28 |
| 13 | 29.7 to 30.6 | 0.582 | | 0.293 | 0.088 | 0.086 | 0.87 |
| | 29.7 to 29.7 | 0.000 | Yes | 0.331 | 0.084 | 0.110 | 0.03 |

| Group | Mile Markers | P-Value for T-Test with Unequal Means | Boundary where Statistically Significant at 99.9% | Standard Deviation | Mean | Variance | Miles |
|-------|--------------|---------------------------------------|---|--------------------|-------|----------|-------|
| 14 | 28.9 to 29.7 | 0.000 | Yes | 0.451 | 0.143 | 0.203 | 0.73 |
| 15 | 28.7 to 28.9 | 0.113 | | 0.485 | 0.193 | 0.235 | 0.25 |
| | 26.5 to 28.7 | 0.000 | Yes | 0.373 | 0.178 | 0.139 | 2.20 |
| 16 | 25.4 to 26.5 | 0.000 | Yes | 0.489 | 0.326 | 0.239 | 1.08 |
| 16 | 25.2 to 25.4 | 0.000 | Yes | 0.304 | 0.099 | 0.092 | 0.24 |
| 18 | 24.2 to 25.2 | 0.433 | | 0.280 | 0.043 | 0.078 | 0.92 |
| | 23.2 to 24.2 | 0.000 | Yes | 0.260 | 0.039 | 0.068 | 1.06 |
| 19 | 23.2 to 23.2 | 0.300 | | 0.231 | 0.015 | 0.053 | 0.01 |
| | 22.6 to 23.2 | 0.052 | | 0.148 | 0.010 | 0.022 | 0.59 |
| | 22.2 to 22.6 | 0.920 | | 0.073 | 0.005 | 0.005 | 0.43 |
| | 22.1 to 22.2 | 0.908 | | 0.086 | 0.005 | 0.007 | 0.04 |
| | 21.9 to 22.1 | 0.753 | | 0.087 | 0.005 | 0.008 | 0.21 |
| | 20.7 to 21.9 | 0.499 | | 0.101 | 0.006 | 0.010 | 1.21 |
| | 20.7 to 20.7 | 0.582 | | 0.127 | 0.007 | 0.016 | 0.01 |
| | 16.0 to 20.7 | 0.432 | | 0.093 | 0.006 | 0.009 | 4.66 |
| | 15.8 to 16.0 | 0.621 | | 0.130 | 0.008 | 0.017 | 0.25 |
| | 15.3 to 15.8 | 0.001 | | 0.124 | 0.007 | 0.015 | 0.47 |
| | 14.5 to 15.3 | 0.000 | Yes | 0.214 | 0.019 | 0.046 | 0.81 |
| 20 | 14.0 to 14.5 | 0.586 | | 0.270 | 0.040 | 0.073 | 0.53 |
| | 13.8 to 14.0 | 0.632 | | 0.293 | 0.044 | 0.086 | 0.19 |
| | 13.4 to 13.8 | 0.000 | Yes | 0.270 | 0.041 | 0.073 | 0.42 |
| 21 | 13.1 to 13.4 | 0.255 | | 0.375 | 0.073 | 0.141 | 0.30 |
| | 11.6 to 13.1 | 0.000 | Yes | 0.311 | 0.065 | 0.097 | 1.42 |
| 22 | 11.1 to 11.6 | 0.000 | Yes | 0.468 | 0.124 | 0.219 | 0.54 |
| 23 | 10.5 to 11.1 | 0.200 | | 0.338 | 0.084 | 0.114 | 0.62 |
| | 10.0 to 10.5 | 0.861 | | 0.410 | 0.094 | 0.168 | 0.53 |
| | 9.9 to 10.0 | 0.000 | Yes | 0.371 | 0.093 | 0.138 | 0.10 |
| 24 | 8.9 to 9.9 | 0.729 | | 0.387 | 0.037 | 0.150 | 0.94 |
| | 8.4 to 8.9 | 0.884 | | 0.384 | 0.034 | 0.148 | 0.49 |
| | 8.1 to 8.4 | 0.663 | | 0.374 | 0.033 | 0.140 | 0.35 |
| | 8.0 to 8.1 | 0.669 | | 0.320 | 0.029 | 0.102 | 0.05 |
| | 7.6 to 8.0 | 0.167 | | 0.372 | 0.033 | 0.139 | 0.43 |
| | 7.5 to 7.6 | 0.904 | | 0.422 | 0.045 | 0.178 | 0.10 |
| | 7.1 to 7.5 | 0.949 | | 0.425 | 0.044 | 0.180 | 0.40 |
| | 6.0 to 7.1 | 0.000 | Yes | 0.393 | 0.043 | 0.154 | 1.15 |

| Group | Mile Markers | P-Value for T-Test with Unequal Means | Boundary where Statistically Significant at 99.9% | Standard Deviation | Mean | Variance | Miles |
|-------|--------------|---------------------------------------|---|--------------------|-------|----------|-------|
| 25 | 5.8 to 6.0 | 0.544 | | 0.208 | 0.014 | 0.043 | 0.18 |
| | 5.1 to 5.8 | 0.542 | | 0.244 | 0.011 | 0.060 | 0.71 |
| | 4.8 to 5.1 | 0.008 | | 0.185 | 0.008 | 0.034 | 0.23 |
| | 4.4 to 4.8 | 0.667 | | 0.021 | 0.001 | 0.000 | 0.47 |
| | 4.2 to 4.4 | 0.672 | | 0.022 | 0.000 | 0.001 | 0.19 |
| | 3.1 to 4.2 | 0.587 | | 0.010 | 0.000 | 0.000 | 1.10 |
| | 2.7 to 3.1 | 0.975 | | 0.032 | 0.001 | 0.001 | 0.35 |
| | 2.5 to 2.7 | 0.926 | | 0.034 | 0.001 | 0.001 | 0.27 |
| | 1.4 to 2.5 | 0.216 | | 0.031 | 0.001 | 0.001 | 1.03 |
| | 0.9 to 1.4 | 0.554 | | 0.001 | 0.000 | 0.000 | 0.52 |
| | 0.3 to 0.9 | 0.002 | | 0.002 | 0.000 | 0.000 | 0.65 |
| | 0.0 to 0.3 | NA | NA | 0.062 | 0.003 | 0.004 | 0.26 |

Table 4. ANOVA analysis for six segments between MM 39.9 – 43.2

| ANOVA | | | | | | |
|---------------------|----------|----|----------|----------|----------|----------|
| Source of Variation | SS | df | MS | F | P-value | F crit |
| Segments | 1.966228 | 5 | 0.393246 | 1.458947 | 0.199672 | 4.104525 |

CONCLUSION

As probe vehicle data become more reliable, local, state, regional, and national standards need to be established to leverage this data for better congestion management practices. This report proposed a scalable means to characterize congestion called that Travel Time Inflation (TI) performance measure. This performance measure was applied to 68 miles of Interstate-80 in New Jersey. By measuring anonymous probe vehicle speeds along a highway, a threshold to determine when congestion occurs can be established. The TI performance measure accounts for speed variation along a corridor which impact free flow speeds and travel times. Instead of applying a set value, a variable congestion threshold is calculated along a predetermine series of roadway segments called Traffic Message Channels (TMCs)

or Traffic Message Channel (TMC). By establishing a base congestion measure for each TMC segment a more accurate measurement of the increased travel times that accounts for different roadway conditions is established. This is particularly important for a corridor like I-80 that experiences a variety of terrain types, vehicle volumes, and population densities. Because the TI cannot demonstrate the time of day when congestion is occurring, a Corridor Travel Time Inflation (CTI) was established to visualize congestion periods on an hourly and daily basis. Although it is not practical to eliminate all congestion, having a better means to visually document congestion based on individual TMC attributes provides a better method of locating and ultimately managing congestion occurrences.

The problem with using just the TI as a performance measure is that it inherently reflects greater amounts of congestion for longer TMC segments. This makes it difficult to directly compare the congestion characteristics of adjacent TMCs. By normalizing the increase in travel time with the Percent increases in Mean Travel time (PMTT) performance measure, a statistical comparison can be made between adjacent TMCs. A T-Test analysis was performed on the PMTT calculated between adjacent TMCs. The results indicate that of the available TMC segments along the eastbound portion of I-80, there were 25 groups of TMCs that had similar statistical travel time reliabilities. An ANOVA test was applied, and showed that in some instances the results agreed with the T-Test. However, further research will be conducted to compare different statistical methods to group TMC segments and to evaluate the consistency of the groups during PM Peak travel times, seasonal travel, and winter weather travel.

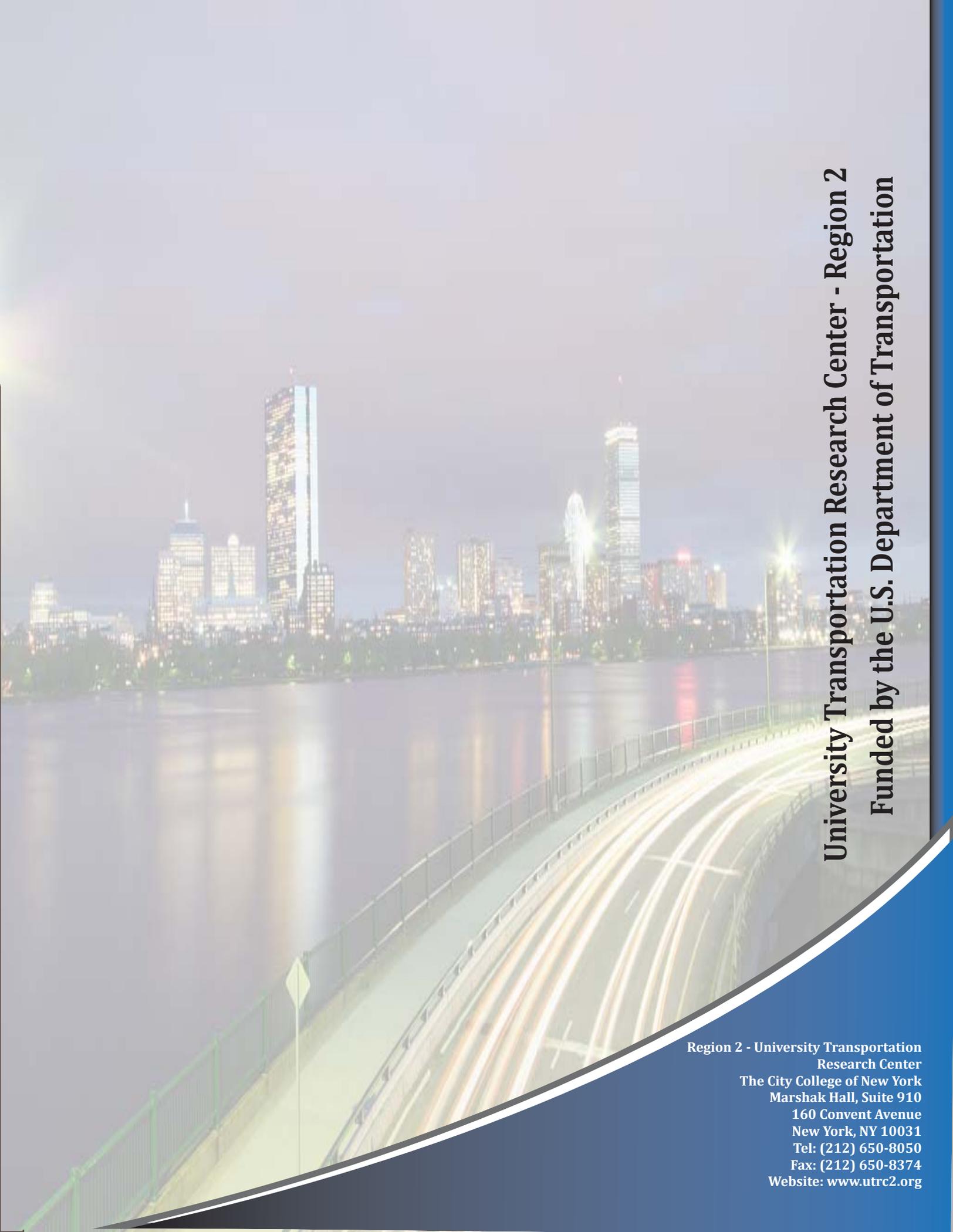
The visualization techniques proposed in the report are an intuitive way to relay the congestion conditions along a corridor to any person who is making decisions regarding capital improvements, construction scheduling, and other roadway management tasks. By consolidating a very large number of speed records for an entire year (Figure 8) into a single picture, a more useable representation of the corridor's performance is developed. Furthermore, by viewing the data in an isometric view (Figure 7 and Figure 9), a better understanding of the magnitude of congestion can be interpreted. The graphical representation of the data also provides a more practical way to archive the data, which can be

referenced in the future by analysts who want to determine how long term capital improvements or policy changes impact a corridor. Ultimately the goal of this type of research is to reduce the overall congestion through better management practices. With a better understanding of where, when, and over what distances traffic congestion is occurring, better management practices and policies can be established.

REFERENCES

1. Brennan, T. M., S.M., Remias and L. Marini, "Performance Measures to Characterize Corridor Travel Time Delay Based on Probe Vehicle Data", Transportation Research Board, Paper number 15-0167, Washington, DC, (2015) IN PRESS.
2. Brennan, T. M., Hainen, A. M., and Remias., (2015). *Characterizing Directional Corridors Based On Probe Vehicle Data*. ITS 23rd World Congress Bordeaux, France (accepted)
3. FHWA, "MAP-21 Moving Ahead for Progress in the 21st Century Act" July 2012
4. ASCE. (2013). *Report Card for America's Infrastructure*, <http://www.infrastructurereportcard.org/roads/> (July 9, 2014)
5. Lomax, T., D. Shrank, B. Eiselee. 2012 Annual Urban Mobility Report. College Station, Texas; The Texas A&M University System, Texas A& M Transportation Institute, 2012.
6. Lomax, T., D. Shrank, B. Eiselee. 2011 Urban Mobility Report Powered by INRIX Traffic Data. College Station, Texas; The Texas A&M University System, Texas A& M Transportation Institute, 2011.
7. Remias S, Brennan T, Grimmer G, Cox E, Horton D, Bullock D. 2011 Indiana Interstate Mobility Report - Full Version. West Lafayette, Indiana: Purdue University, Indiana Mobility Reports; 2012. Report No.: ISBN: 978-1-62260-209-4.
8. Remias S, Brennan T, Day C, Summers H, Cox E, Horton D, Bullock D. 2012 Indiana Mobility Report - Full Version. West Lafayette, Indiana: Purdue University, Indiana Mobility Reports; 2013. Report No.: ISBN: 978-1-62260-257-5.
9. Remias, Stephen, M., T.M. Brennan, C.M. Day, H.T. Summers, D.K. Horton, E.D. Cox and D.M. Bullock, "Spatially Referenced Probe Data Performance Measures for Infrastructure Investment Decision Makers," Submitted to Transportation Research Board, August 1, 2013, Paper No. 14-1062.
10. Maryland Department of Transportation, "2012 Maryland State Highway Mobility Report," July 2012.
11. California Department of Transportation, "Mobility Performance Report 2009", February 2011.
12. Washington State Department of Transportation, "The 2012 Congestion Report," August 2012.
13. Haghani, A., M. Hamdi, K.F. Sadabadi, "I-95 Corridor coalition vehicle probe project: validation of Inrix data July-September 2008-Final Report," I-95 Corridor Coalition. January 2009.
14. Brennan Jr., T.M., S.M. Remias, D.K. Horton, and D.M. Bullock, "Probe Vehicle Based Statewide Mobility Performance Measures for Decision Makers," *Transportation Research Record: Journal of the Transportation Research Board*, 2338(1), 78-90, 2013
15. Brennan, T. M., Day, C.M., Remias, G.M. Horton, D.K., Cox, E.D., Bullock, D. M. (2014). *Alternative Performance Measures and Weighting for Quantifying Spatial and Temporal Congestion using Probe Data*. ITS 21st World Congress

16. Christidis, P., & Rivas, J. N. I. (2012). *Measuring Road Congestion* (No. JRC69961). Institute for Prospective and Technological Studies, Joint Research Centre, Seville, Spain.
17. Lomax, T., et al. "NCHRP report 398: quantifying congestion." *Transportation Research Board, National Research Council, Washington, DC. Final report* (1997).
18. <http://www.erh.noaa.gov/okx/StormEvents/storm02082013.html> (July 10, 2014)
19. Brennan, T.M, D.M. Bullock, "Regional Travel Time Reliability" The 5th International Symposium on Transportation Network Reliability (INSTR2012), 18-19 December 2012, Hong Kong.

A long-exposure photograph of a city skyline at night, reflected in a body of water. In the foreground, a bridge or highway is visible with light trails from moving vehicles. The sky is dark, and the city lights are bright and colorful.

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Funded by the U.S. Department of Transportation

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