University Transportation Research Center - Region 2

Final Report

Incorporating Probe Vehicle Data to Analyze Evacuation Route Resiliency

Performing Organization: The College of New Jersey

April 2018

Sponsor:
University Transportation Research Center - Region 2

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

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:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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Technology Transfer

UTRC's Technology Transfer Program goes beyond what might be considered "traditional" technology transfer activities. Its main objectives are (1) to increase the awareness and level of information concerning transportation issues facing Region 2; (2) to improve the knowledge base and approach to problem solving of the region's transportation workforce, from those operating the systems to those at the most senior level of managing the system; and by doing so, to improve the overall professional capability of the transportation workforce; (3) to stimulate discussion and debate concerning the integration of new technologies into our culture, our work and our transportation systems; (4) to provide the more traditional but extremely important job of disseminating research and project reports, studies, analysis and use of tools to the education, research and practicing community both nationally and internationally; and (5) to provide unbiased information and testimony to decision-makers concerning regional transportation issues consistent with the UTRC theme.

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16. Abstract

Anonymous probe vehicle data has become an important data source to evaluate the performance of highways and arterials roadway systems. By using predefined spatially located segments, Traffic Message Channels (TMCs) and XD Segments, temporal probe vehicle speed data that includes timestamp and an average speed can be collected and analyzed for each segment. This data has been used to develop agency-wide performance measures to better plan and manage infrastructure assets. Recent research has analyzed individual TMC links on roadway systems to identify congested areas along a defined route. Understanding congestion characteristics is especially important when quantifying roadway congestion under extreme conditions like a natural or human-made disaster. This paper demonstrates how probe speed data can be used to assess the impact of a major weather event on coastal roadway networks and major evacuation routes. An analysis of vehicle speed data during Hurricane Sandy (a.k.a Super Storm Sandy), the second costliest hurricane in the United States is used to demonstrate the methodologies presented in the paper. The evacuation analysis encompasses 1518 TMCs, including 13 evacuation routes, within 10-miles of the New Jersey coast. An additional analysis was conducted on a subset of the 1518 TMCs to develop a regional congestion performance measure using 614 TMCs. Approximately 90-million speed records covering nine counties where analyzed in the study. The results quantified when and where data connectivity decreased during the storm and its eventual recovery.

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FIGURES

TABLES

ABSTRACT

Probe vehicle speed data has become an important data source for evaluating the congestion performance of highways and arterial roads. Predefined spatially located segments known as Traffic Message Channels (TMCs) are linked to commercially available, temporal anonymous probe vehicle speed data. This data has been used to develop agency-wide performance measures to better plan and manage infrastructure assets. Recent research has analyzed individual TMC links on roadway systems to identify congested areas along a defined route. Understanding congestion characteristics is especially important when quantifying roadway congestion under extreme conditions like a natural or human-made disaster. This paper demonstrates how probe speed data can be used to assess the impact of a major weather event on coastal roadway networks and major evacuation routes. An analysis of vehicle speed data during Hurricane Sandy (a.k.a Super Storm Sandy), the second costliest hurricane in the United States is used to demonstrate the methodologies presented in the paper. The evacuation analysis encompasses 1518 TMCs, including 13 evacuation routes, within 10-miles of the New Jersey coast. An additional analysis was conducted on a subset of the 1518 TMCs to develop a regional congestion performance measure using 614 TMCs. Approximately 90-million speed records covering nine counties where analyzed in the study. The results quantified when and where data connectivity decreased during the storm and its eventual recovery.

EXECUTIVE SUMMARY

The New Jersey coast was used as a study site to evaluate how the transportation network performed before, during, and after Hurricane Sandy (a.k.a Super Storm Sandy). Predefined spatially located segments known as Traffic Message Channels (TMC) are linked to commercially available, temporal anonymous probe vehicle speed data. By measuring both the availability of the data, as well as congestion performance metrics derived from vehicle speeds, the effects of the mandatory evacuation where graphically illustrated. As vehicles evacuated, the data available diminished along with the recurring congestion. As vehicles returned to the coast, the congestion returned along with data feeds from each TMC. One week after the storm there was at least one TMC not reporting data because it was impassable; a result of the storm. By evaluating both the congestion as well as the absence of data a quantifiable evaluation of the infrastructure was defined. By comparing the variable free flow travel time evaluated on a fixed length highway segment, each of which is associated with temporal anonymous probe vehicle data, a means to evaluate infrastructure resiliency before and after a major storm event was established. A complete paper based on this research is found in the compendium of papers for the ITS World Congress in Montreal, CN (Titled: *Incorporating speed data to analyze evacuation route resiliency*, *Paper # AM-SP0892*).

The research also demonstrates that the Regional Increase in Mean Travel Time (RIMTT) can be used to visually evaluate the traffic congestion on a regional level using the same anonymous probe vehicle speed data. By quantifying the fluctuations in travel time as compared to a base free flow speed, a systematic evaluation of the disaggregated as well as regionally aggregated congestion along multiple corridors was established. A complete paper based on this research is currently in press in the Transportation Research Record (Titled: *Performance Measures for Characterizing Regional Congestion Using Aggregated Multiyear Probe Vehicle Data*)

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INTRODUCTION

In 2011, Hurricane Irene had destroyed a number of roadways in Vermont and New Hampshire making it difficult to know what roads were open (1). With the help of Google Inc., within 24-hours Vermont posted an Internet map of all the road closures to let motorists know how to traverse the system. The roadway damage was documented by Vermont Transportation scouts (2), which required the maps to be updated three times per day. Probe vehicle data offers a viable means to enhance the ability of relevant agencies to update maps and determine roadway performance in real time during a number of types of transportation events. Recent research conducted at Purdue University has used these data sets to determine crash occurrences on a highway (*3*). By leveraging new information technologies the changing roadway conditions can be understood more quickly and thus decrease the response time needed to mitigate a problem (*4*). Since 2010 the fidelity of probe vehicle data has improved greatly and now includes highways, arterials, and local roads with data collected from both public and private crowd sources (5). The ability to obtain speeds for smaller roadway segments is fast becoming a viable means to evaluate a transportation system on a granular level. Probe vehicle data has been used in national mobility reports (6, *7*) and statewide mobility reports of interstates as well as pre-defined commuter corridors using different performance measures (5, *8*, *9*, *10*, *11*, *12*, *13*).

On October 29, 2012 Sandy, the second most expensive hurricane at the time in United States history, made landfall on the coast of New Jersey. The total cost attributable to the storm exceeded $71 Billion (*14*), it destroyed over 100,000 homes, and caused at least 132 deaths (*15*). This research uses archived probe vehicle data to analyze the impact of hurricane Sandy on New Jersey's coastal transportation system. The research methods apply previously defined performance measures (16) to demonstrate how probe data can be used to assess the impact and recovery of a regional transportation system after a natural disaster. The evacuation analysis encompasses 1518 TMCs, including 13 evacuation routes, within 10-miles of the New Jersey coast.

This research also employed archived probe vehicle speed data to analyze the evolving congestion characteristics of the coastal region of New Jersey over the same two-week periods of 2012, 2013, 2014, and 2016. This additional analysis was conducted on a subset of the 1518 TMCs to develop a regional congestion performance measure using 614 TMCs. Regional performance measures are demonstrated along with a data drill-down to determine the spatial relationships of areas having the highest impact on the region. Although this research explores historic speed data, the methodologies presented can be applied to real-time speed data to assist first responders, residents, and freight vehicles that need to traverse a disconnected system during an emergency event. Approximately 90-million speed records covering nine counties where analyzed in the study.

DATA

The mechanism for processing probe vehicle speed data requires a cross reference between spatially defined Traffic Message Channels (TMC) and commercially available temporal TMC speed data sets. Each TMC is defined by spatial attributes and a corresponding roadway ID; an example of these attributes is shown in Table 1. An example of the speed records, associated with each TMC, is shown in Table 2. Each speed record is accompanied by a time-date stamp, C-value, and confidence score. A confidence of 30, along with a c-value of 100, indicates that the speed is directly based, not calculated, on probe vehicle measurements. For this research, only records with a score of 30 and c-value of 100 were included.

Table 1 TMCs available for NJ-Route 138

TMC	Road	Direction	Length (miles)	Start Lat.	Start Long.	End Lat.	End Long.
120-07527	NJ-138	WEST	0.946374	40.17121	-74.0749	40.17059	-74.0928
120N07527	NJ-138	WEST	0.055516	40.17059	-74.0928	40.17056	-74.0938
120-07526	NJ-138	EAST	0.264959	40.17056	-74.0938	40.17058	-74.0988
120N07526	NJ-138	EAST	0.135502	40.17058	-74.0988	40.17051	-74.1014

Table 2 Example TMC speed data

TMC	Date Time Stamp	SMS (MPH)	Confidence Score	C-Value
120-07527	10/29/2012 12:30	74	30	100
120N07527	10/30/2012 12:30	71	30	100
120+07526	10/31/2012 12:30	7	30	100
120P07526	11/1/2012 12:30	13	30	100

To quantify the general congestion over a region, an evaluation of all TMCs located within 10 miles of the coast of New Jersey was analyzed (Figure 1). The study area shown in Figure 1 is comprised of 1518 TMC segments. The regional analysis includes all types of roadways include highways, arterials, and local roads. For the TMCs shown in Figure 1, approximately 45 million speed records were analyzed. In addition the macro regional analysis, a micro evaluation New Jersey Department of Transportation (NJDOT) defined evacuation routes is also conducted. There are 32 defined evacuation routes (*17*), only 13 of which are collecting speed data along a defined TMC, see Figure 2.

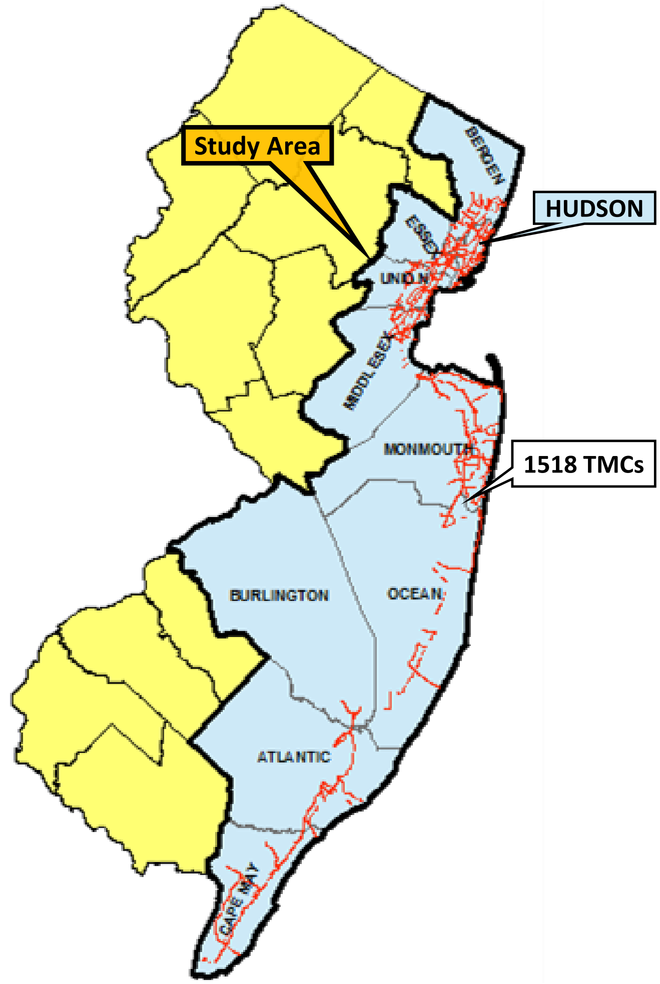
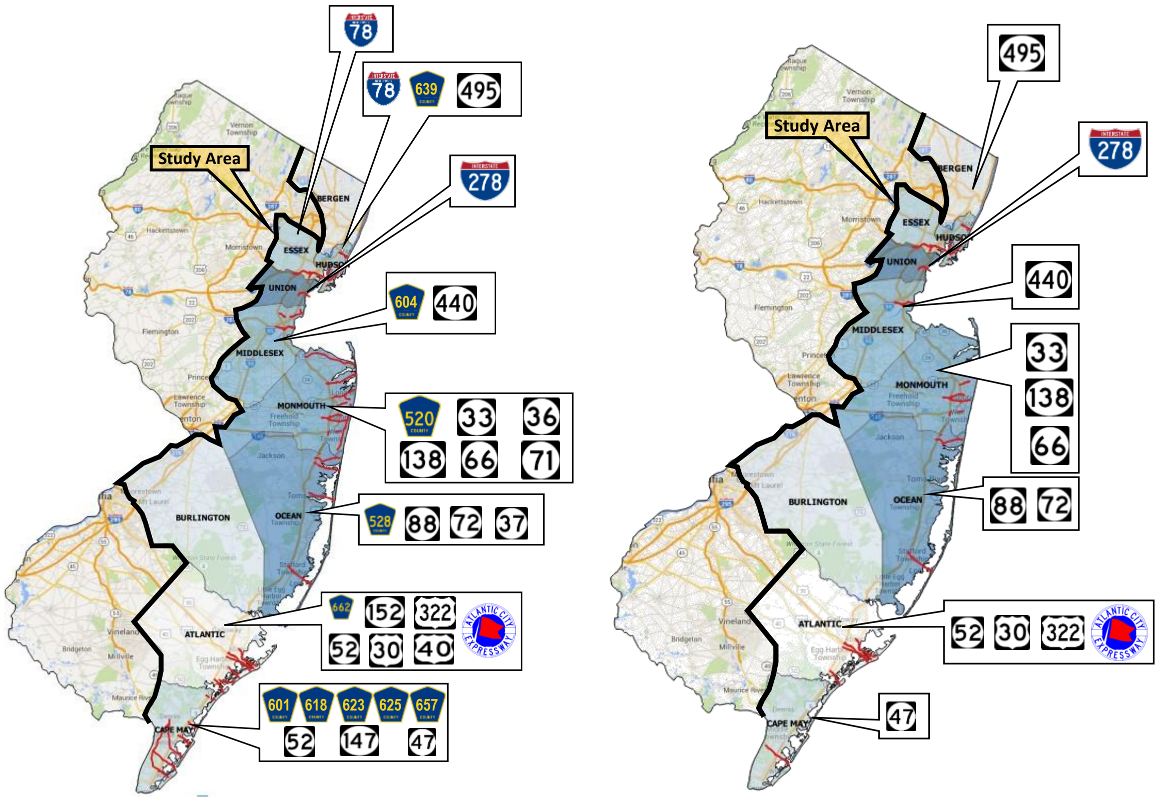


Figure 1. Study area along the Atlantic Coast of New Jersey with 1518 TMC segments receiving data (October 20, 2012).



a) Evacuation routes - 32

b) Evacuation Routes with Traffic Message Channel Data - 13

Figure 2. New Jersey hurricane evacuation routes by county within 10 miles of the Atlantic coast

TRAVEL TIME INFLATION AS A MEASURE OF CONGESTION

Previous research has considered any TMC to be congested during a period of time when the calculated Space Mean Speed (SMS) falls below a pre-defined speed, typically 45 mph for major highways (5, *8*, *18*, *19*). Using a fixed speed threshold does not account for variations in the road geometry, spatial location, and roadway type. This is especially important when determining the congestion thresholds along the coastal routes where posted speeds are much lower than speed limits on a typical highway. Therefore, this research uses a variable threshold defined for each TMC to compare against each calculated SMS over a 15-minute period (*16*). The variable speed threshold is 70% of the calculated Base Free Flow Speed (BFFS) and 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 in miles per hour (MPH), n_{ij} is the total count of the 15-minute SMS bins between 0200 and 0600 for June 2012, v_{ij} is the SMS for a specific segment *i* during a period of time *j*, and the 0.70 represents 70% of the calculated value. The June 2012 (0200-0600) timeframe was chosen because there is a reasonable amount of shore traffic during this time of year that can provide an accurate measure of the BFFS. Both the time frame and the 0.70, can be adjusted based on regional requirements. Previous studies had used 45 MPH as the fixed speed threshold, which is approximately 70% of 65 MPH (*4*, *8*). In addition, the 0.70 was used in previous research (*16*) and is being used here to demonstrate how probe vehicle data can be used to assess the hurricane's impact.

For this project, each TMC is assigned a base travel time (BTT) that accounts for the TMC's length and observed 70% BFFS. The base travel time for each TMC is defined in the following (*16*):

$$BTT_i = \frac{x_i}{v_{ia}} \quad (2)$$

where, BTT_i is the base travel time in hours for TMC *i* and x_i is the distance in miles for the TMC. The travel time for any TMC segment is defined as follows:

$$TT_{ij} = \begin{cases} \frac{x_i}{v_{ij}}, & v_{ij} < v_{ia} \\ 0, & v_{ij} \geq v_{ia} \end{cases} \quad (3)$$

where, TT_{ij} is travel time in hours of TMC *i* at time period *j* and v_{ii} and v_{ia} are as defined in equation 1 The total travel time, Travel Time Inflation (TI) performance measure, was used because it accounts for TMCs length and speed variability inherent with spatial location and roadway type. TI is the difference between the BTT and TT as shown in the following equation:

$$TI_i = \sum_{j=1}^{n} (TT_{ij} - BTT_i) \quad (4)$$

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.

By aggregating the TI values over a three-week period, which includes the day of the storm event and comparing the data from 2012 to 2013, a representation of the relative congestion intensity from week to week can be observed. The results of this performance analysis are shown in Figure 3. From the figure, a definitive decrease in the overall congestion was observed during the week of October 28, 2012. When compared to 2013, there is a fairly steady amount of congestion from week to week in the months of October and November. This may be an indication that motorists are not using the roadways in 2012 and/or the roadways are unusable. A subsequent finer analysis of the daily TI is shown in Figure 4, where traffic is dramatically lower on the day-before, day-of and day-after Hurricane Sandy, when compared to the traffic on the same dates/day of week the following year (2013).

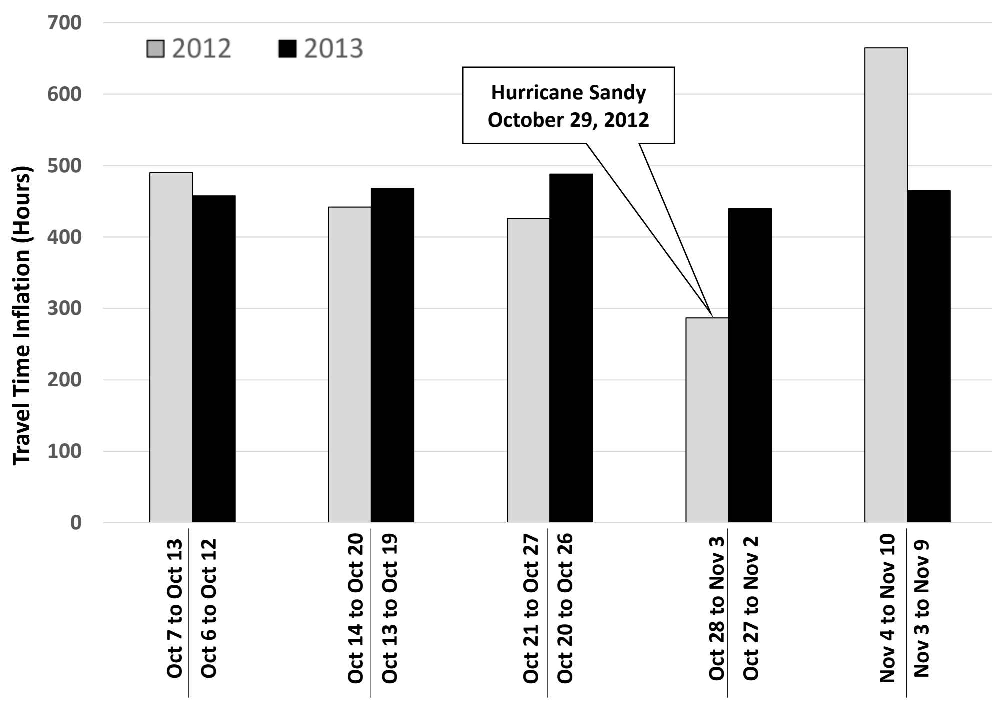


Figure 3. Comparison of Travel Time Inflation (hours) for 1518 TMC segments located within 10 miles of coast for 2012 and 2013.

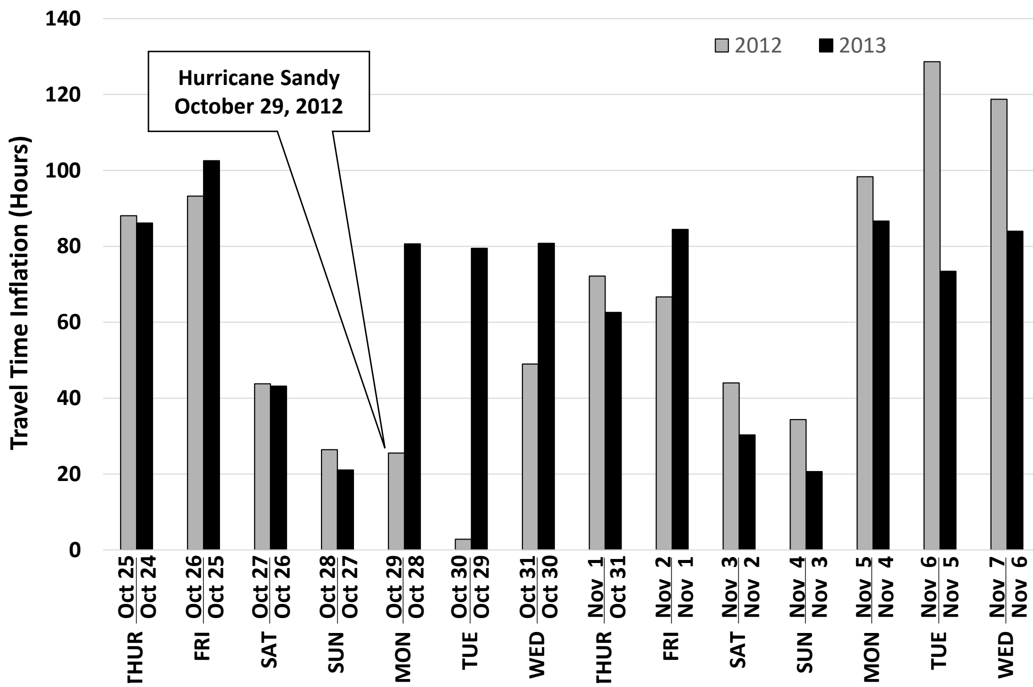


Figure 4. Total hours of Daily Travel Time Inflation (TI) for Study Area.

The abrupt decrease in aggregated TI for the nine counties (Figure 3 and Figure 4), may be indicative of a couple of possibilities pertaining to the data collected. The first is that no vehicles are traversing the segment or at least the number of vehicles has decreased to a point that no congestion is occurring. This can be caused by a detour or a decrease in the normal volume of vehicles being carried by the roadway caused by some abnormal event. The other possibility is that the segment cannot be traversed because of a road closure or some other hindrance preventing data from being collected on a segment.

Data on all 1518 segments were also analyzed during a 12-hour period (0700 – 1900) from October 21 to November 3, 2012 to determine the type of congestion occurring in the study area defined in Figure 1. During the week of the hurricane (October 28 to November 3) it is evident that there are certain times of day when traffic would not be present on a segment, while in the preceding week it may have been available. To quantify this, when the 15-min data are available for the preceding week (e.g. Sunday October 21), but not available for the following week (e.g. Sunday October 28), a binary indicator was assigned to that segment for that time period. If a segment has a value of 48 (there are a total of 48, 15-minute bins during a12-hour period) for a particular day it is assumed that no data was collected on that segment. By observing these values for each day on each segment, the recovery of the system could be observed. This data is shown in Figure 5, where the day following the hurricane, about 14% or 213 of the TMC segments did not collect data, while in the preceding week data was available.

Although there is still one TMC with no data being collected on Friday 11/2/2012, most of the TMCs are observed to be collecting some data, which indicates vehicles are traversing the segment. From the graph, the recovery of the system based on data collected on Saturday 11/3/2012 is about the same as the Sunday, the day before the hurricane, 10/28/2012. The segment locations where data is not being collected can be spatial represented on a map (Figure 6). From the figure, there were a total of 760 segments, collecting zero and or less than three hours of data on October 30, 2012. This decrease in data collected corresponds to the decrease in TI in Figure 3 and Figure 4. Also shown in the figure are the five TMC segments reporting less than 3 hours of congestion on November 3rd. With regard to Ocean County, the Route 72 Bridge entering the barrier island was still closed as per a New Jersey Transcom report (*20*). Such additional information provides insight into why some areas have no segment data being collected after the storm. Approximate 85% of the 1518 TMCs were collecting more than 6 hours of traffic data within a week of the storm.

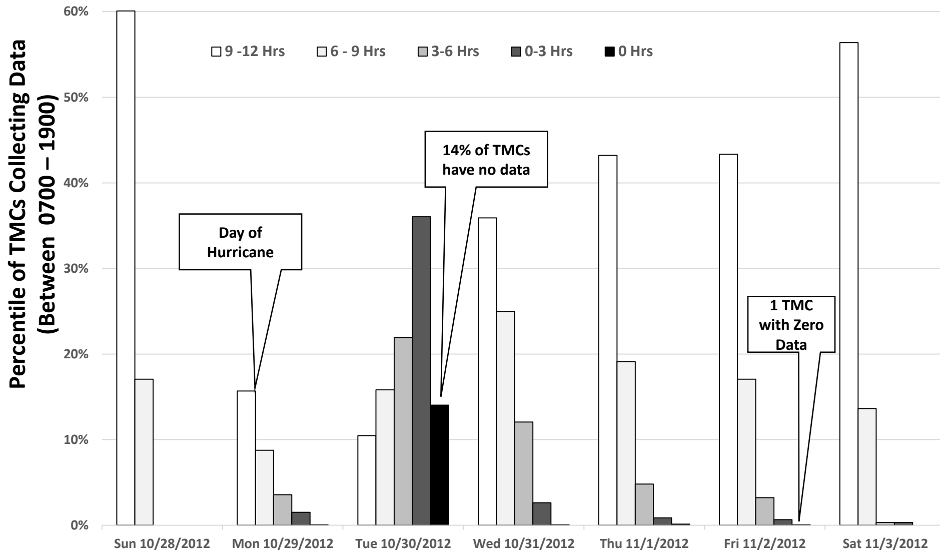


Figure 5. Percentage of Segments Collecting Data Between 0700 – 1900 during the week of October 28, 2012.

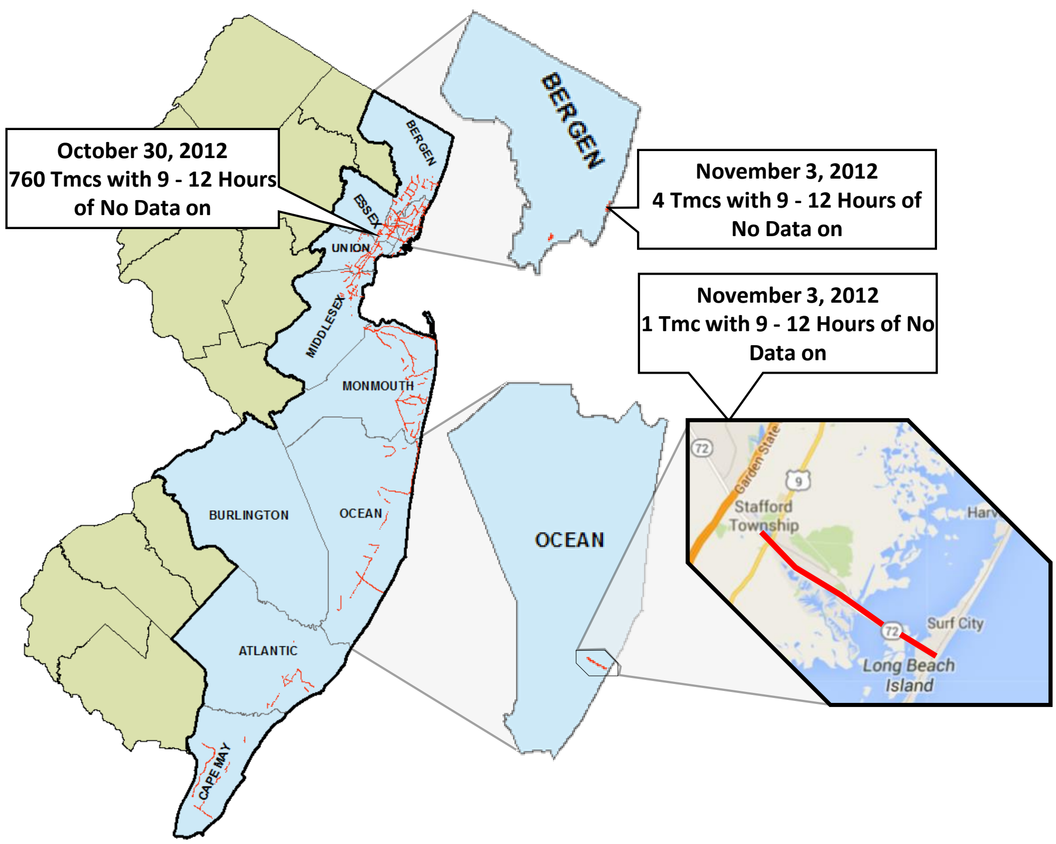


Figure 6. Spatial mapping of available probe vehicle segment data on October 30 and November 3, 2012.

Corridor-Level Travel Time Inflation

After taking a macroscopic view of the region, a microscopic inspection of the evacuation routes was conducted. Of the 32 evacuation routes define by shown in Figure 2a, only 13 were covered by TMCs. Of the 13 evacuations routes that normally have data, NJ state route 72 (Figure 6) is the only route with no probe vehicle data during and immediately after the storm (20) due to closure

> "*Police department activity on NJ 72 eastbound from Marsha Dr (Stafford Twp) to CR 607/Long Beach Blvd (Ship Bottom) all lanes closed and detoured until further notice*".

To better understand the dynamics of individual evacuation routes, New Jersey Route 138 was selected for further analysis. New Jersey Route 138 1.7 miles consisting of five TMCs (Table 1) adjacent to the Garden State Parkway was provided (Figure 7). To evaluate this route, the Corridor Travel Time Inflation (CTI) performance measure was used. The Corridor Travel Time Inflation (CTI) equation is adapted from earlier research (*4*, *8*, *18*) and defined in the following (*16*):

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

The *CTI* (hours) is the summation of all of the TIs within a series of TMC segments. Using this performance measure, a series of TMC segments *S* for time periods *T* on this 1.7-mile portion of westbound NJ-138 can be characterized and illustrated (Figure 8). As seen in the figure, for the week before, and the week of the storm the calculated travel time inflation metric does not appear to indicate any congestion. However, in the week after the storm a significant amount of congestion is observed. This may be interpreted as a good indication of traffic movement in the westbound direction especially when compared to the 2013 data, but further analysis of the data is necessary to determine exactly when and why congestion was observed the week after the storm.

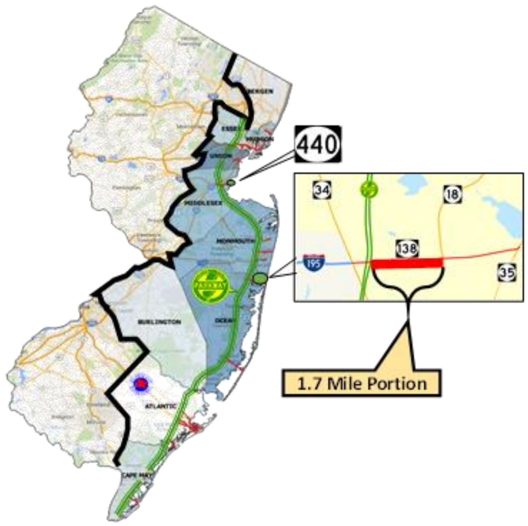


Figure 7. NJ-138 evacuation corridor between the coastal regions and the Garden State Parkway.

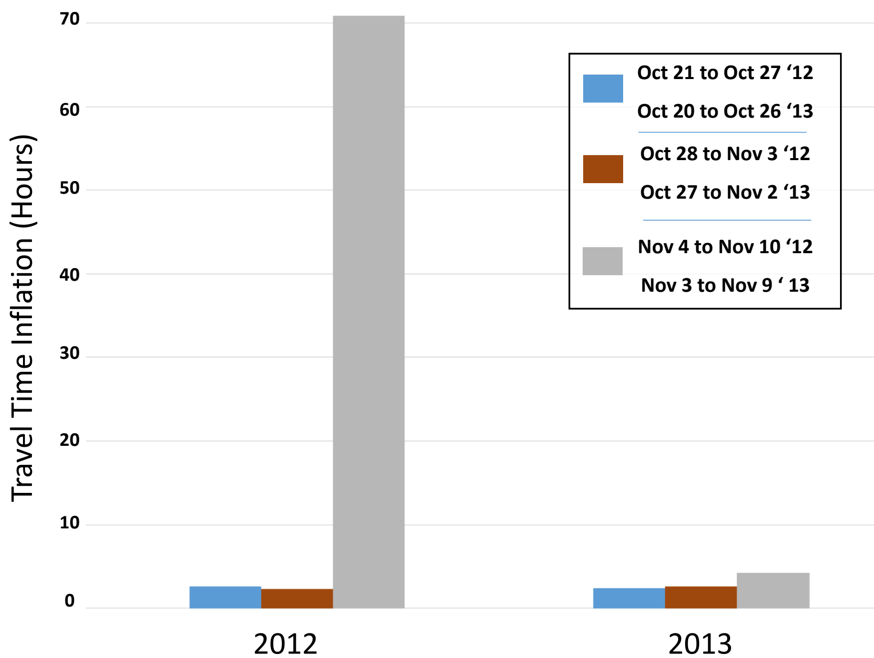


Figure 8. Corridor Total Travel Time Inflation Hours for Westbound NJ-138 Visualization of Corridor Travel Time Inflation

A 17-day example depicting the increase in travel time over a 1.7-mile portion of NJ-138 is shown in Figure 9. This figure illustrates how the corridor reacted during the storm event. The color contour bands in the figure represent the CTI minutes (*21*). Notable observations from the figure are as follows:

- During October 29 and 30, data is still being collected along the corridor. This is indicated by the minor bumps labeled on the figure as 'Minor Congestion'. The absence of any bumps in CTI could indicate lack of data. From this figure, it appears data were collected during and immediately after the storm.

- On November 7, and incident occurred around 1630. Based on NJDOT crash records, a crash incident did occur on SR-138 at mile post 0.7 under snowy conditions. This appears to be the reason for increase in CTI shown in Figure 8.

An additional example of this type of trend visualization is shown in Figure 10, were a 4.9-mile portion of NJ-440 is represented. Visualizing the CTI data in this manner allows a temporal representation of congestion. Such representation allows trends to be seen over the course of a day or week and allows the observer to have a better understanding of when and where congestion is occurring even on a small corridor. The measures developed in this research have been applied to highways, but as the data becomes more frequent and more accurate real-time mapping of corridor congestion will be produced.

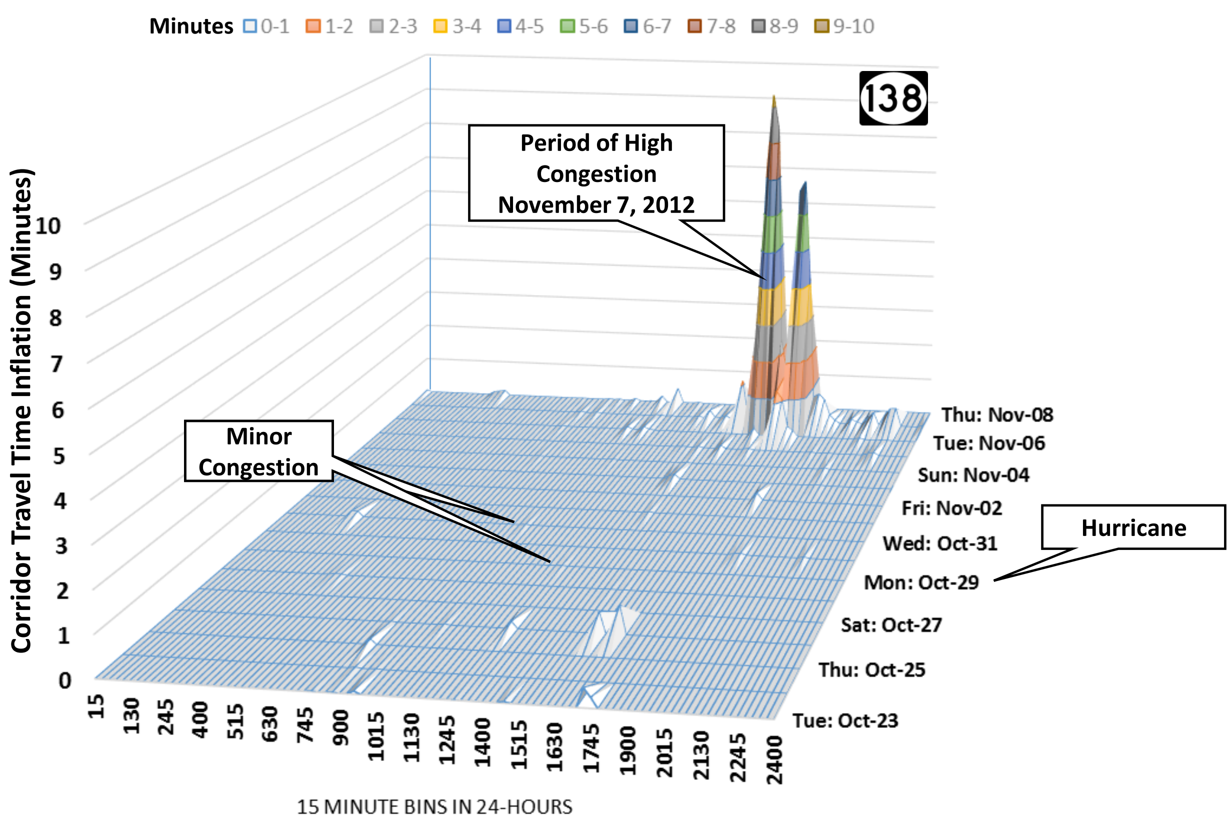


Figure 9. Seventeen day example of 24-hour plots of Corridor Travel Time Inflation for 1.7 mile portion of westbound NJ-138, 2012.

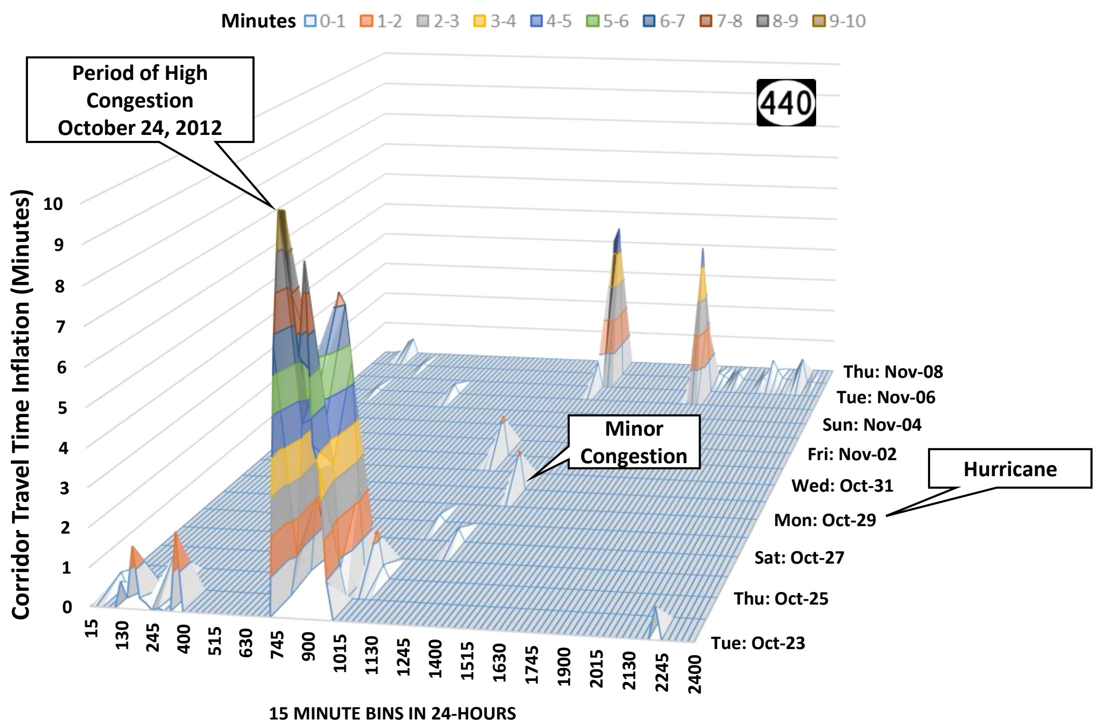


Figure 10. Seventeen day example of 24-hour plots of corridor travel time inflation for 4.9 mile portion of westbound NJ-440, 2012.

Regional Travel Time Inflation Applied to New Jersey Coast

The region is defined by selecting all TMCs reporting data located within 10 miles of the coast of New Jersey (Figure 1). Other regions, and the methods for selecting regions will be defined in future research, but for this study only the coast is selected to demonstrate the methodologies proposed. The focused regional study area shown in Figure 11 is comprised of 614 TMCs, or about 3.8% of the state's 16,256 TMCs. The regional analysis encompasses all types of roadways including major highways, arterials, and local roads. To aggregate TI on a region level, a regional performance measure is defined as shown in Equation 8:

$$RTI = \sum_{i \in R} TI_i \qquad 8$$

where, *RTI* is the total travel time inflation for all TMC segments *i* in the analysis region *R* within the analysis period defined in Equation 4. In summary, the RTI is the aggregation of all the increased travel time incurred on all TMCs within a region.

The demonstration of the regional performance measure provides a high level aggregate analysis of the regional pulse of the transportation network. This aggregation begins with RTI (Equation 8), but can subsequently be disaggregated to the individual TMC's TI value (Equation 4) to better understand what is impacting the region's roadway system. The RTI provides macro-characterization of the relative congestion intensity. This is demonstrated in Figure 12, where a week-to-week comparisons are made to determine fluctuations in RTI during the 2012 storm and the comparable periods in subsequent years. As seen in the figure, the storm's impact is observed during the week of October 28, 2012. There is a notable increase in RTI during the week after the hurricane, while in subsequent years it remained relatively steady. The increase in 2012 may be an indication that motorists are heading back to the coast to clean up after the storm and/or that there has been a decrease in the infrastructure's ability to handle capacity. Also, there was a dramatic increase in the TI from 2013 to 2014, and from 2014 to 2016.

A subsequent analysis of the daily RTI is shown in Figure 13, where traffic is lower the day-of and day-after Hurricane Sandy, when compared to the traffic on the same dates/day of week the following year (2013). Traffic volumes were higher on the day before the 2012 hurricane compared to the same period in 2013, potentially indicating an increase in congestion due the mandatory evacuation put in place on Sunday October 28, 2012.

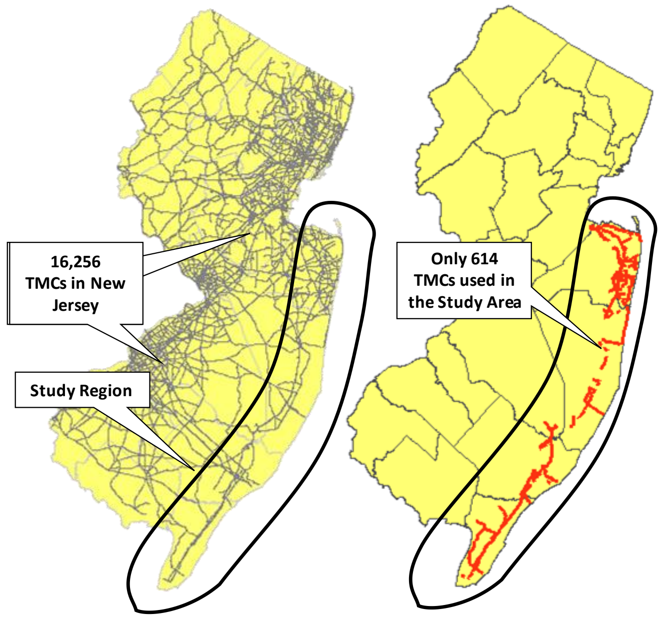


Figure 11. Study area along the Atlantic Coast of New Jersey with 614 TMC segments.

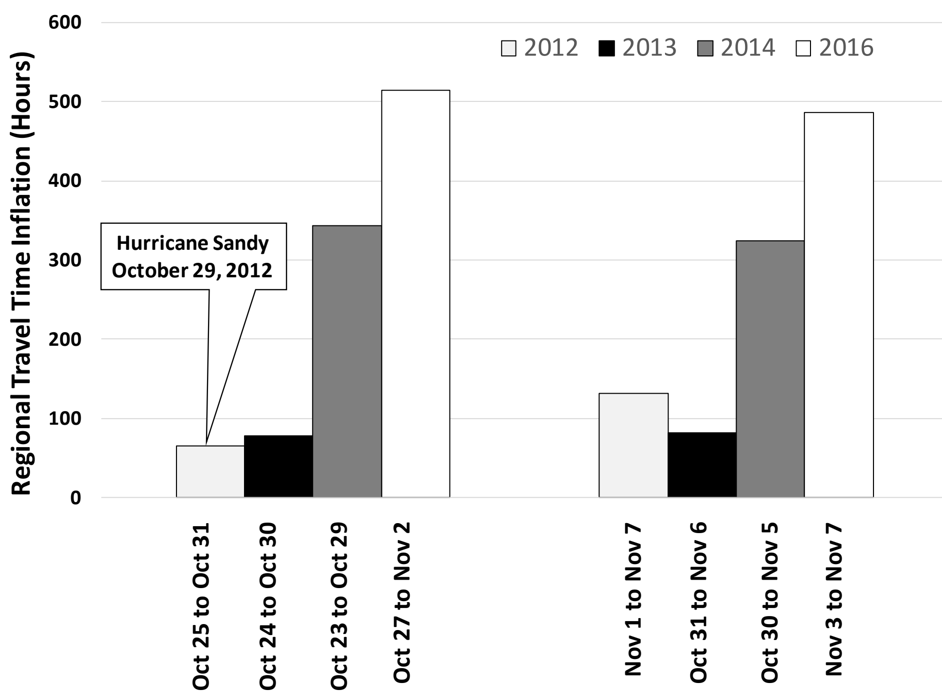


Figure 12. Total hours Weekly Regional Travel Time Inflation (RTI) for study area during 2012, 2013, 2014, and 2016.

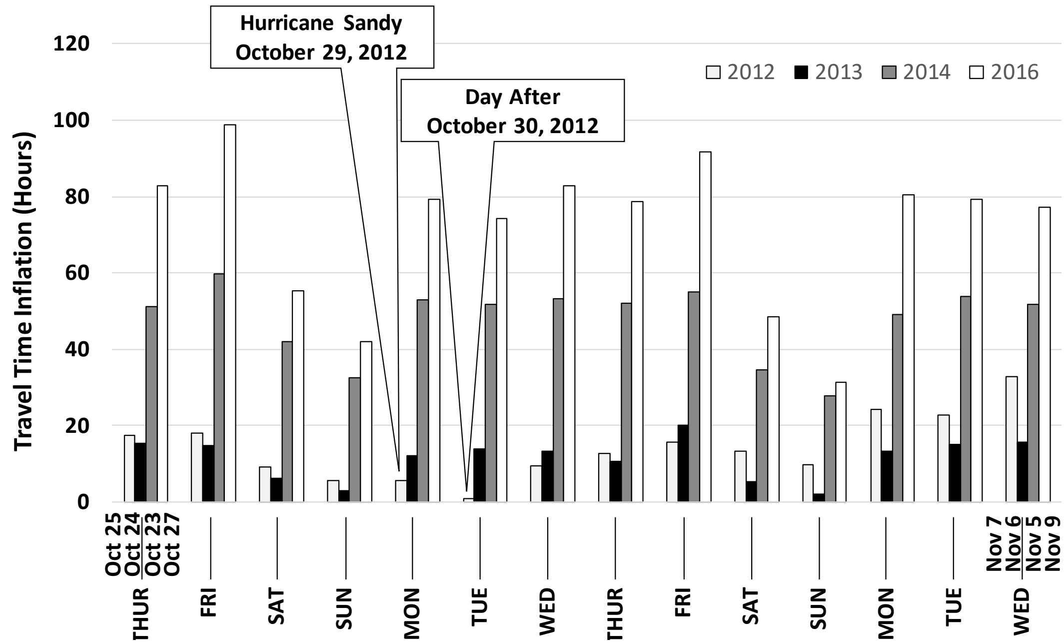


Figure 13. Total hours of Daily Regional Travel Time Inflation (RTI) for Study Area during 2012, 2013, 2014, and 2016.

REGIONAL CONGESTION DISTRIBUTION

To quantify the congestion derived from each of the TMCs in Figure 11, the calculated TI (Equation 4) was used to create a histogram comparing each TMC's disaggregated TI over the two-week study period. This analysis (FIGURE 14) indicates that a small shift in the TI, can have a dramatic impact on the RTI. For instance, in 2016, where the highest RTI is observed (Figure 14), there was a shift in the number of TMCs with a travel time inflation of 4, 6, and 8. The RTI indicated that there was an increase in the regional congestion, while the TI mapped the locations where the congestion is worse.

In the years following the hurricane, no other major events were recorded during the two-week study periods. Therefore, in 2013, 2014, and 2016, the increase in congestion is likely due to an increase in the recurring and construction type congestion as reflected by the increased TI on each TMC. To better understand the TI distribution, a spatial representation of the year-to-year change is shown in Figure 15. The observations noted on Figure 15 support the RTI analysis reflected in Figure 12 and

Figure 13. They also demonstrate how the RTI data can be disaggregated to show where areas of high congestion are located in the region.

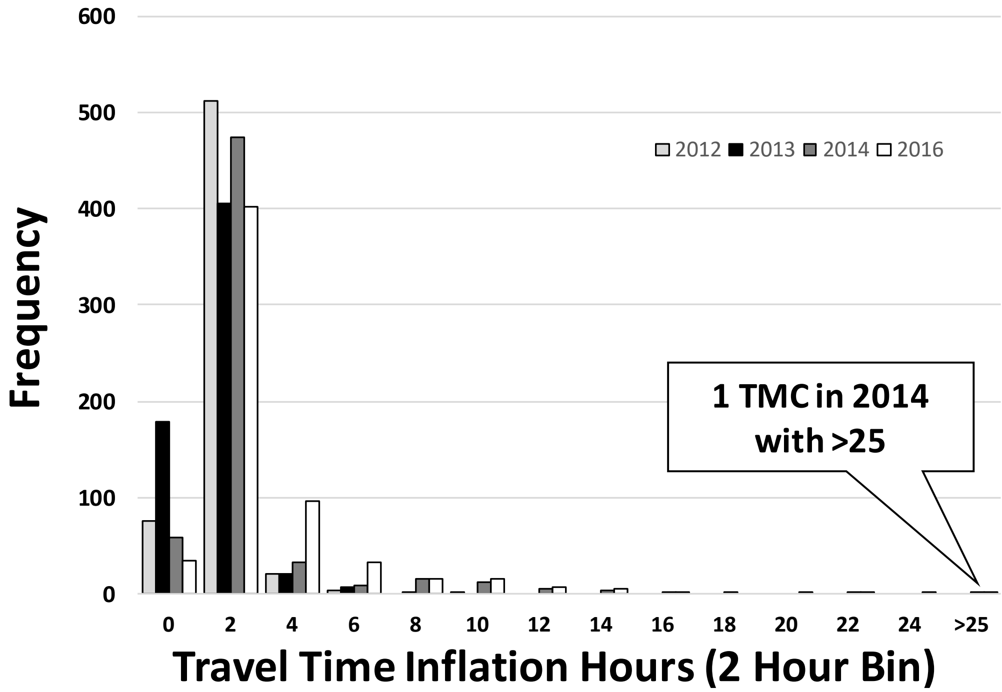


Figure 14. Number of TMCs reporting TI for 2012, 2013, 2014, 2016.

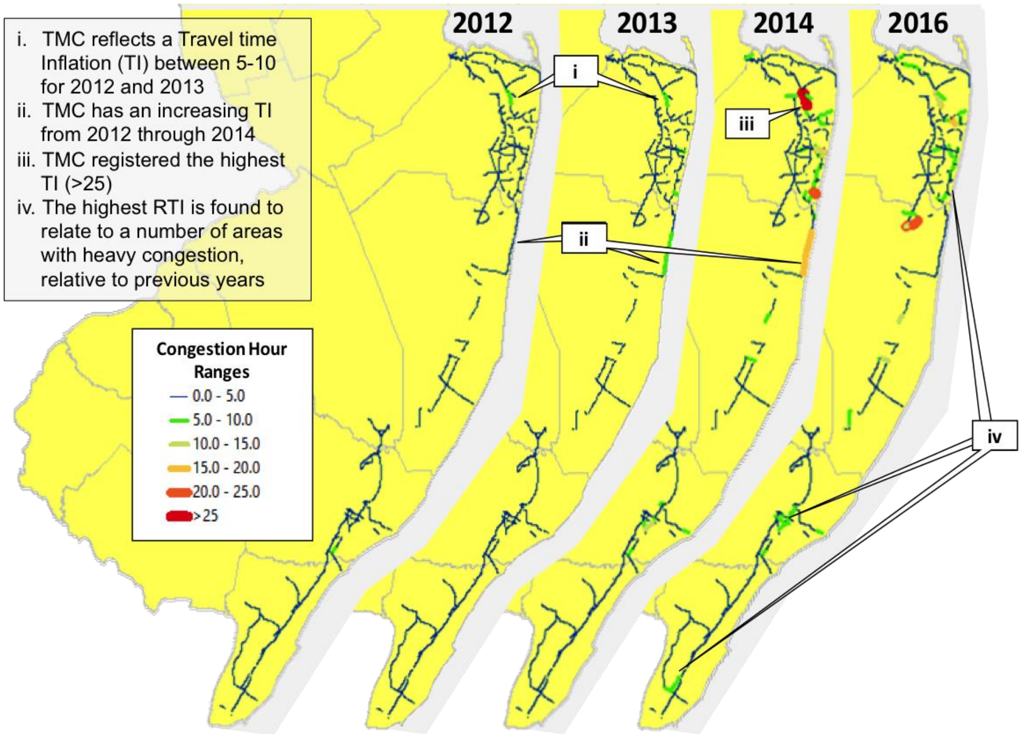


Figure 15. Two weeks of aggregated TI for 2012, 2013, 2014, 2016. Regional Yearly Congestion

Although the locations of increased RTI could be qualitatively observed (as shown in Figure 12 and Figure 13) for shorter durations, it would be difficult to represent this data over an entire year. The RTI may be used an indicator for the region which characterizes the degree of congestion experienced by drivers as a function of the increase in travel time. To view the region's data over an entire year, and compare the day to day congestion, the TI for each TMC is normalized with respect to the TMC's base travel time, yielding the Regional Increase in Mean Travel Time (RIMTT):

$$RIMTT_{ij} = \sum_{n} \frac{TI_i}{BTT_i} \quad (9)$$

where RIMTTij is defined for a TMC segment i for a 15-minute bin time period j and TI_i is defined in Equation 4. For the RIMTT performance measure all the TI values are aggregated for every TMC in 15-minute bins. A representation of this performance measure for 2016 is shown in Figure 16, where a number of events occurring in the region are identifiable from the data visualization. The range of values in the figure is 0 to 5 ,meaning that the increase in travel time ranges for 0 times to 5 times the typical travel time within the region. From the figure, winter storm Jonas in January is identified as well as the summer holidays; Memorial Day, Fourth of July, and Labor Day weekend. All of these holidays were expected to increase congestion considering the region is a major summer destination in New Jersey. Other notable observation from this figure include an increase in congestion during the evening hours, data loss on August 15, and a noticeable drop in congestion on December 25. This method can be used to observe the region and characterize the congestion throughout the year. Further research is necessary to compare multiple regions and year to year congestion.

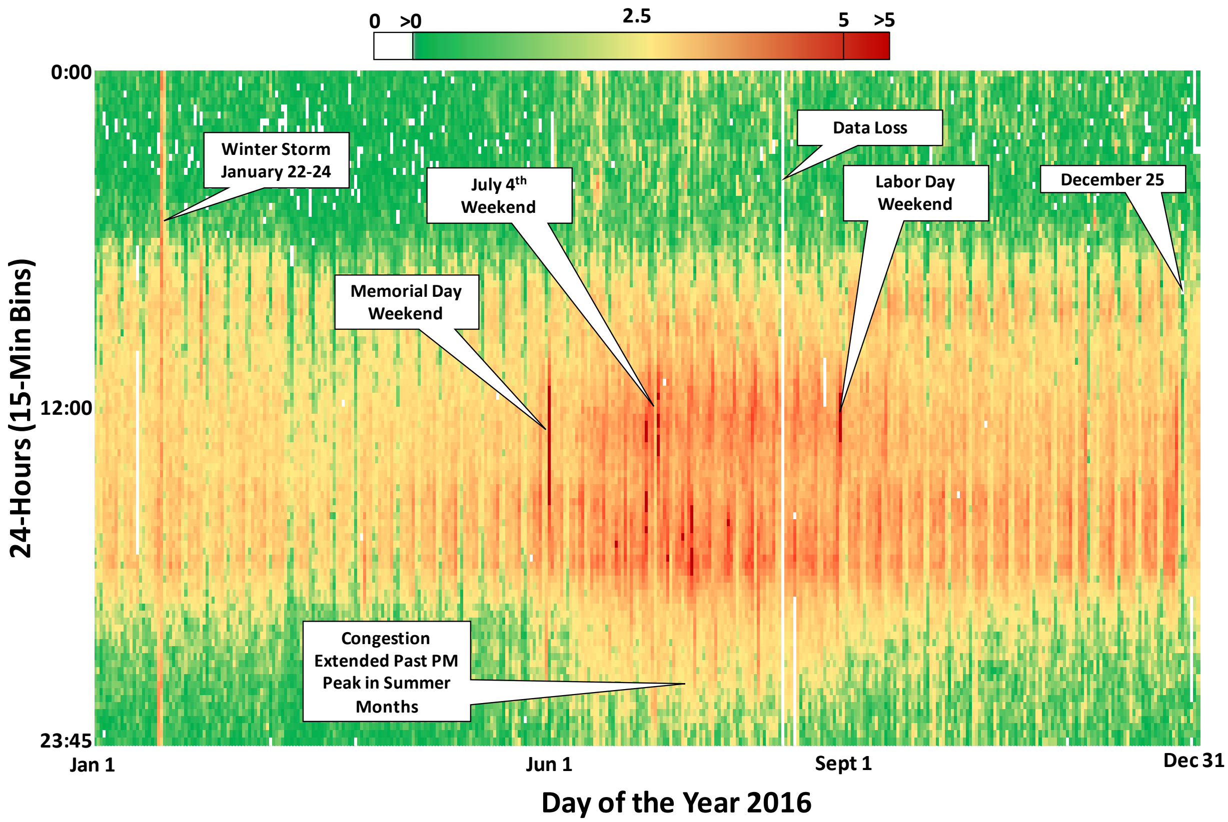


Figure 16. Daily RIMTT in 15-min bins for 2016

CONCLUSIONS

This report applied a scalable Travel Time Inflation (TI) performance measure to evaluate roadway segments with probe vehicle data located within 10 miles of the New Jersey coast. The time period surrounding Hurricane Sandy was used to demonstrate how probe vehicle data could be used to assess the impact of severe weather events on the entire system before, during, and after major event. These types of performance measures are proving to be vital for regional transportation reports. Based on the results, it appears that some of the same methods used to evaluate highway congestion can be used to quantify the impact of a natural disaster. With only 13 out of the 32 costal evacuation routes having some form of probe data available, it is apparent that not enough roadway segments are being monitored by probe vehicles. Although currently available data may be sufficient for evaluation of arterials for normal performance measurement of highways, the data does not cover critical roadways that connect coastal towns to major roadways like the Garden State Parkway.

This research also applied a scalable Regional Travel Time Inflation (RTI) performance measure that quantifies the increase in travel time experienced by motorists. The measure was used to aggregate probe vehicle speed data to characterize the congestion in a region within 10 miles of the New Jersey coast, thus providing a high level characterization of the region's congestion. The RTI is derived from the Travel Time Inflation (TI) performance measure, which was used to determine the spatial distribution of congestion throughout the region. These performance measures (RTI and TI) were derived for the study area during the same two-week periods in 2012, 2013, 2014, and 2016. The results show that the probe vehicle speed data, when aggregated as either RTI or TI, can act as a performance measure for characterizing congestion on a dispersed transportation network.

An additional exploratory indicator, the Regional Increase in Mean Travel Time (RIMTT) was also developed to characterize the yearly congestion in 2016. RIMTT, which provides a mechanism to gauge daily congestion in 15-minute intervals, is not a performance measure. Rather, it is a visualization technique that relays information that makes the probe vehicle data particularly useful. From the visualization created by the RIMTT data, specific events could be observed throughout the year as well as the changes in congestion throughout the day. This type of visualization has been applied to individual highways, but not to a region (13,16).

As probe vehicle data become more reliable, local, state, regional, and national standards need to be established to leverage this data to produce ongoing monitoring of the transportation system. These types of standards are especially important during a natural or manmade disaster. This is evident in North Carolina, where are a power outage caused by a construction error required the evacuation of over 10,000 tourists (24). The application of this type of data in real time can help improve disaster management processes by determining where and when a response should be made by an agency and evaluating how the transportation system recovers from a disaster (23). With improved data collection, the ability to visualize traffic conditions in real time can assist first responders, residents, and freight vehicles traverse a disconnected system during an emergency event. This data can also be used to validate the need, or determine the impact, of infrastructure investment.

New Jersey is a densely populated state with a large shoreline making a larger portion of the population more susceptible to a natural disaster like a hurricane or even a high tidal surges that can disrupt the transportation system. Further research will explore the implementation of an automated system that uses anonymous probe vehicle data to help manage the existing transportation system. This type of system, once in place, will prove a more proactive means of managing the transportation system during a manmade or natural disaster.

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