



Visualizing and Evaluating Interdependent Regional Traffic Congestion and System Resiliency, a Case Study Using Big Data from Probe Vehicles

Thomas M. Brennan Jr.¹ · Ryan A. Gurriell¹ · Andrew J. Bechtel¹ · Mohan M. Venigalla²

Received: 2 November 2018 / Revised: 27 February 2019 / Accepted: 4 March 2019 / Published online: 5 April 2019
© Springer Nature Singapore Pte Ltd. 2019

Abstract

Big data from probe vehicles is increasingly becoming an important contributor for determining the regional performance of a transportation roadway network. Recent research has applied aggregated speed data from probe vehicles to quantify travel time variations as a result of recurring congestion, incidents, weather events and other non-recurring congestion. Through the establishment of a base travel time for all roadway segments in a region, any increase in travel time characteristics in the regional networks can be quantified temporally and spatially. This characterization is especially important when determining a region's congestion resiliency, which is being defined as the ability of a roadway network accommodate failures and return to a baseline congestion after a major capacity reduction to the roadway network. This paper demonstrates how aggregated big data on vehicle speeds obtained from regionally deployed probe vehicles could be used to characterize and visualize the interdependent congestion impacts between regions and across roadway types (interstate, arterial, and local). To demonstrate the models and methodologies, an in-depth analysis of the I-276 Bridge closure incident in Burlington County, NJ near Philadelphia, PA was conducted. The bridge was closed after a routine inspection identified a crack in one of the structural members. In total, 90 days of data, which included 90-million speed records, were commercially collected for 1765 roadway segments, was analyzed. A novel performance metric was developed to allow an impact analysis by comparing Burlington County to two adjacent counties, Mercer and Camden. The results showed that the bridge closure did have a definitive, quantifiable impact on the primary road network of the adjacent counties. Subsequent analysis identified specific roadways that were most impacted by the closure. Although this research explores historic speed data, the methodologies presented can be applied to real-time speed data to assist in developing efficient traffic operation plans during major incidents, lane closures and weather events.

Keywords Traffic performance measures · Big data · Infrastructure resilience · Probe vehicles

Introduction

Analysis of the performance of expansive road transportation networks requires copious quantities of speed and flow data. Traditional data sources for roadway performance measures are traffic counts, spot-speed studies and travel-time studies. These sources provide very limited data in terms of temporal and spatial coverage. In contrast, anonymous probe vehicles are currently acquiring big data repositories that are rich in spatial and temporal dimensions over the vast majority of the nation's roadways. These big data repositories are increasingly being used in transportation analytics and in the development of key performance measures. For example, the Texas A&M Transportation Institute (TTI) incorporates probe vehicle data in the annual publication of the

✉ Thomas M. Brennan Jr.
brennant@tcnj.edu

Ryan A. Gurriell
gurrier1@tcnj.edu

Andrew J. Bechtel
bechtela@tcnj.edu

Mohan M. Venigalla
mvenigal@gmu.edu

¹ The College of New Jersey, 2000 Pennington Road, Ewing, NJ 08628, USA

² George Mason University, Fairfax, USA

Urban Mobility Report, which ranks urban congestion levels throughout the United States (Schrank et al. 2015). Probe vehicle data have been used in national mobility reports (Lomax et al. 2011, 2012) and statewide mobility reports of interstates as well as pre-defined commuter corridors using different performance measures (Remias et al. 2012, 2013, 2014; Maryland 2012; California 2009; Washington 2012; Haghani et al. 2009). Recent research has used probe vehicle data to develop quantified regional performance measures along with visually intuitive graphical representation of large data sets (Brennan and Venigalla 2017; Brennan et al. 2018a). Probe data have also been used to evaluate the impact on the roadway network after a natural disaster (Brennan et al. 2018a; Hara and Kuwahara 2015). Collective congestion performance measures on a regional level provide a means to determine the impact of planning, operation decision, and overall resiliency to better determine future decisions regarding construction, detours, and may provide insight as to how to focus capital improvement funds to better manage the system as a whole. Visualization methods are necessary to convey meaning of large data sets. The importance of “information visualization” is well characterized by the following quote (Few 2009):

“Most data analysis involves searching for and making sense of relationships among values and making comparisons that involve more than just two values at a time. To perform these operations and see relationships among data, which exhibit themselves as patterns, trends, and exceptions, we need a picture of the data.” (Page 30.)

While probe vehicle data are currently being adopted due to its expansive and continuous nature, it only respond as a symptom of existing problems, and it is not well understood how it respond to different stimuli. Pack (2012) developed a web-based visual analytics monitoring system for identifying major bottlenecks, reporting on travel time reliability, and displaying other congestion measures using private sector vehicle probe data fused with agency incident/event data where available. The system included probe data from as early as 2008 through early 2012. The data were used to analyze trends from year-to-year, month-to-month, and day-to-day.

This paper evaluates how the archived anonymous probe vehicle speed data reacted to the I-276 bridge closure between New Jersey and Pennsylvania. Approximately 90-million speed records covering three adjacent counties in New Jersey were analyzed in the study. The data ingestion and analysis software used to evaluate the 90-million records are briefly described. The research methods build on previously defined performance measures (Brennan et al. 2015, 2018a, b, 2019; Brennan and Venigalla 2017) to demonstrate how aggregated probe data can be used to

assess the congestion due to, and recovery from, a major impact on the roadway network across a region to evaluate the region’s roadway network resiliency. Motorists know where they want to go, but agencies need to recognize if the choices are viable and if the road network can handle additional, unexpected traffic. The research presented measures that are used to determine if a regional impact has occurred, whether it is statistically significant, and where the congestion impacts are occurring (county, interstate, arterials, local roads, townships, etc.). The first step is to know if the region is reacting, where it is reacting, and how much is it reacting as compared to normal operation. The performance measures developed quantify the increase in travel time experienced by the motoring public, as well as the interdependent congestion impacts between regions and across roadway types (interstate, arterial, and local) in a visually intuitive manner. With known volumes and classification of traffic, these performance metrics can be used to quantify the actual cost to the motoring public as well as the environmental impact caused by congestion over a region. This study did not obtain traffic volume information, however, this type of research has been conducted in previous studies (Day et al. 2012). This paper outlines the data process used to develop a methodology for evaluating the interdependent congestion relationship among roadway types and across agency boundaries before, during, and after a major, unexpected, bridge closure.

Data

The evaluation of commercially available anonymous probe vehicle speed data requires a cross reference between spatially defined traffic message channels (TMC) and temporal speed data sets. These data are collected by a commercial provider who tracks vehicle telematics over predefined TMCs. Each TMC is geo-located and assigned a corresponding unique roadway ID. The format of this data has been defined in previous research (Brennan and Venigalla 2017; Brennan et al. 2018a, b, 2019). Each speed record includes a time-stamp, *c*-value, and confidence score as its attributes. A confidence score of 30, along with a *c*-value of 100, indicates that the speed is directly based, not calculated, on probe vehicle measurements with a high confidence that the speed represents the actual roadway conditions. For this research, only records with a score of 30 and *c*-value of 85 or greater, which indicates an 85% confidence that the actual roadway conditions are represented, were included. There were a few instances when zero data were collected, but these only occurred for a total of 6-h over the 90-day study, or 0.28%. Except for these 6-h, the data with a level of 30 and an 85% confidence were available. The missing 6-h of data were excluded from the analyses.

The study region is defined by selecting all TMCs within three New Jersey counties, namely Mercer, Camden, and Burlington counties, located in the close proximity of the Pennsylvania (PA)/New Jersey (NJ) Turnpike Bridge crossing (I-276), shown in Fig. 1. The study area (Fig. 1) is comprised of 1765, or about 10.8% of the state’s 16,256 TMCs. The regional analyses were categorized to include the New Jersey Department of Transportation (NJDOT)-maintained roads (Interstates and Arterials) and local roads that are not maintained by NJDOT. The data were collected between January 1, 2017 and March 31, 2017 to cover the bridge closure and subsequent reopening. The I-276 Bridge was abruptly closed on Friday January 20, 2017 (Argos 2019) due to a failure in a structural member, leaving six of the seven regional bridges open for traffic. The congestion impact of this bridge closure was felt regionally. The data employed in the big data analytics for assessing the impact of this event included over 90 million unique speed records. The 1765 unique TMCs and their respective attributes (length, common name, and jurisdiction) were imported as relational database model ingested into a Microsoft Standard Query Language (MSSQL) server. The historic speed data for the study period was also added. Each TMC segment was associated with its respective speed records. The entire database was then indexed to increase query speed. To facilitate the database model the data were consolidated into 15-min bins and organized into a data structure using MatLAB. The

data were structured using the following fields: TMC ID, year, month, day, and 15-min bin. This data structure allows the data to be quickly accessed on a daily, monthly, and yearly level.

Measures of Congestion

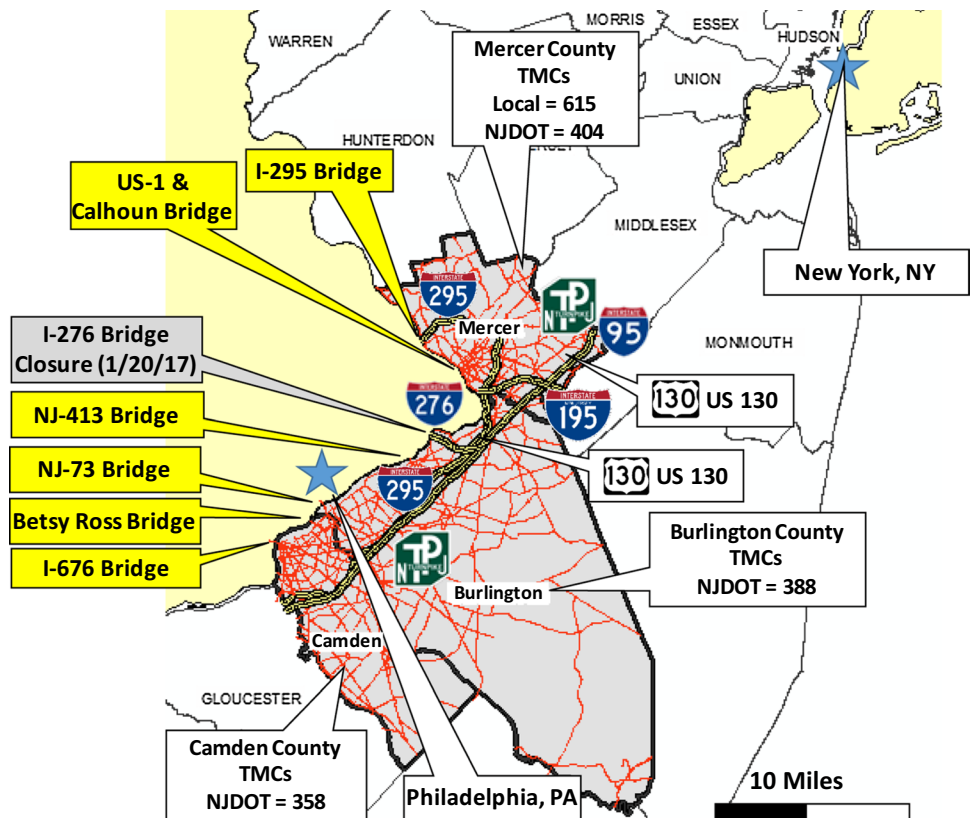
To evaluate changes in travel speed throughout the data, a base level of performance represented by the anonymous probe vehicle data needed to be established. Base free-flow speed for each TMC was determined by calculating the average segment speed during 0200–0600 h when congestion due to volume is unlikely (Brennan et al. 2018a, b). The base free flow speed (BFFS) is calculated as follows:

$$BFFS_i = \frac{1}{n_j} \sum_{j \in F} v_{ij}, \tag{1}$$

where BFFS is the variable speed threshold for TMC i ; v_{ij} are speed records for TMC i for the 15-min interval j ; n_j is the total count of 15-min intervals within the free-flow time F , which is defined as all of the minutes between 0200 and 0600 during the entire 90-day study period.

The BFFS was used for all time periods analyzed. It should be pointed out that even though the BFFS measure used in this research is similar in concept with BFFS

Fig. 1 Three-county study area (New Jersey, USA) around the I-276 Bridge closure with 1765 TMC segments



defined in the Highway Capacity Manual (Highway Capacity Manual 2016), the computation is different. Both the analysis time frame and the percent speed threshold can be adjusted to better understand how the regional transportation system reacts and recovers under recurring conditions as well as extreme events.

Additionally, each of the 1765 TMCs is assigned a base travel time (BTT) that accounts for the TMC’s length and its observed BFFS. The base travel time for each TMC is computed using Eq. 2 (Brennan et al. 2018a, b):

$$BTT_i = \frac{X_i}{BFFS_i}, \tag{2}$$

where BTT_i is the base travel time in hours for TMC i and X_i is the distance in miles for the TMC

Previous research (Brennan and Venigalla 2017, Brennan et al. 2018a) had included a 70% reduction in base free flow speed to calculate the travel time which defined congestion conditions, but for this research the calculated BTT was used as a baseline for determining when any increase in travel time occurred. The calculated travel time for any TMC segment is defined as shown in Eq. 3:

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

where TT_{ij} is travel time in hours of TMC i at time period j and v_{ij} and $BFFS_i$ are as defined in Eq. 1. Anytime v_{ij} is less than $BFFS_i$, a travel time was calculated.

For total travel time a travel time inflation (TI) performance measure, which accounts for TMC length and speed variability inherent with spatial location, was used (Brennan et al. 2018a, b). TI is the difference between the BTT and TT as shown in Eq. 4:

$$TI_i = \sum_{j \in A} (TT_{ij} - BTT_i); \quad \text{for } TT_{ij} > 0, \tag{4}$$

where TI_i is the total travel time inflation for TMC segment i for all 15-min intervals within analysis period A .

Thus, every 15-min interval where the travel time exceeds the segment-defined threshold base travel time leads to an accumulation of TI. The variable TI represents individual TMC travel time inflation. 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):

$$RIMTT_{ij} = \sum_n \frac{TI_i}{BTT_i}, \tag{5}$$

where $RIMTT_{ij}$ represents the increase for TMC segment i for a 15-min time interval j and TI_i is as defined in Eq. 4.

For the RIMTT performance measure all the TI values are aggregated for every TMC in 15-min bins. Previous research has used this metric to demonstrate the regional impact of Hurricane Sandy (Brennan and Venigalla 2017; Brennan et al. 2018a). To normalize the RIMTT to view the aggregated data between counties or regions, the total number RIMTT is divided by the number of TMCs (Fig. 1) located in each county dependent on what is being analyzed is defined as follows:

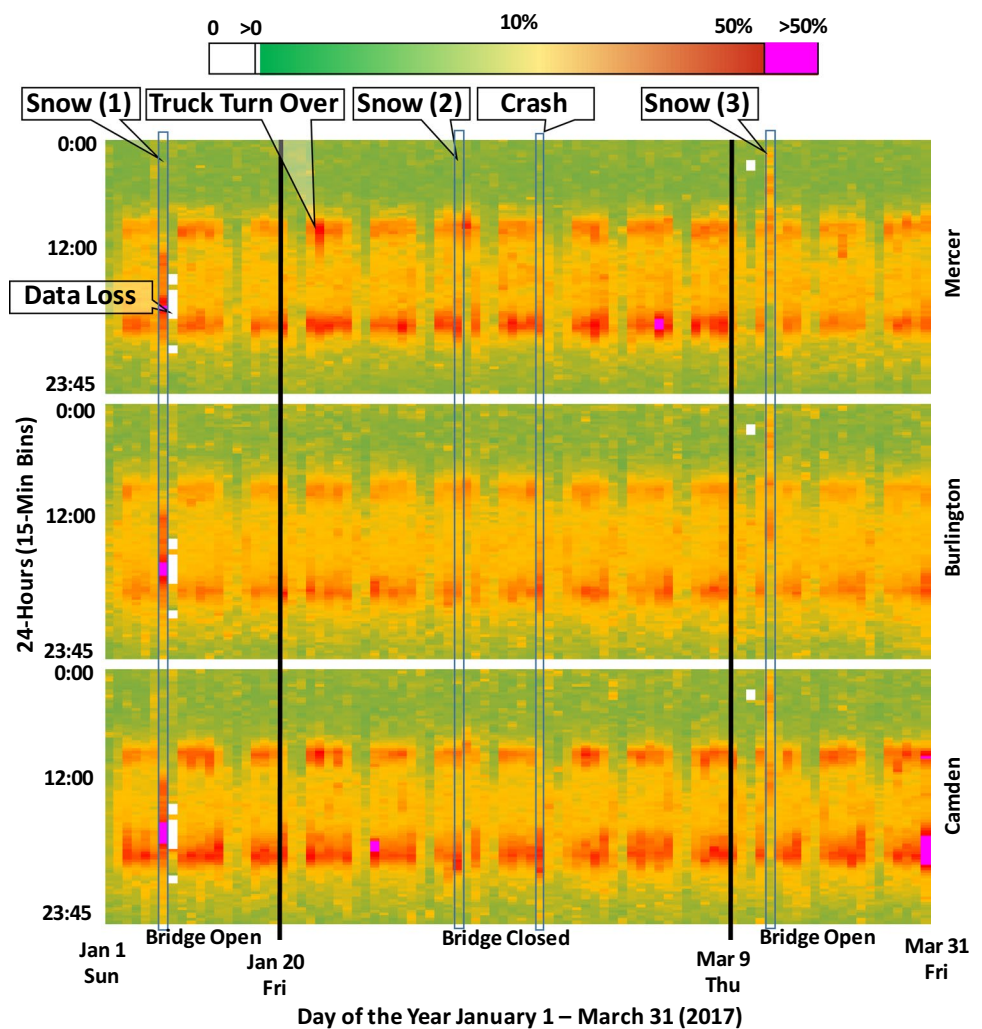
$$MTT_{cj} = \frac{RIMTT_{ij}}{TMC_c} \times 100, \tag{6}$$

where MTT_{cj} is the mean percent increase in TMC travel time for all TMCs in a county region c , during a 15-min time interval j .

Mean Percent Increase in TMC Travel Time: A Case Study Applied to the I-276 Bridge Closure

The MTT provides a means to evaluate and compare the impact of traffic-related events traversing regional transportation network boundaries. The I-276 Bridge was abruptly closed on Friday January 20, 2017, when a structural member was found to be cracked (Argos 2019). To determine the impact on the three adjacent counties, the MTT was applied. The visualization of MTT is provided in Fig. 2 for all NJDOT-maintained roadways in Mercer, Burlington, and Camden County, NJ. The graph shows the juxtaposing of the counties, each with a 24-h y-axis in 15-min increments. To illustrate the difference before and after the bridge closure, a color scale was chosen where a 50% increase in MTT is considered to be the upper end of the scale. The 50% is an arbitrary number that can be adjusted based on an agency’s requirement. For this study, the 50% increase in MTT adequately illustrated the bridge closure. The following observations can be noted from this illustration (Fig. 2)—all but one of them apply to all counties, some impacting a single county, while other impacted each of the counties.

- All counties: three snow days are observed in all counties
- All counties: areas shown to be ‘white’ are locations when no data were available.
- All counties: the weekend traffic versus the weekday traffic.
- All counties: AM Peak and PM Peak travel times are identified.
- All counties: road closure on US-130 due to crash incident (Route 130 2017)
- Mercer County: Dump Truck Turn over on I-195 (Brown 2019)

Fig. 2 MTT for NJDOT-maintained roadways (1150 TMCs)

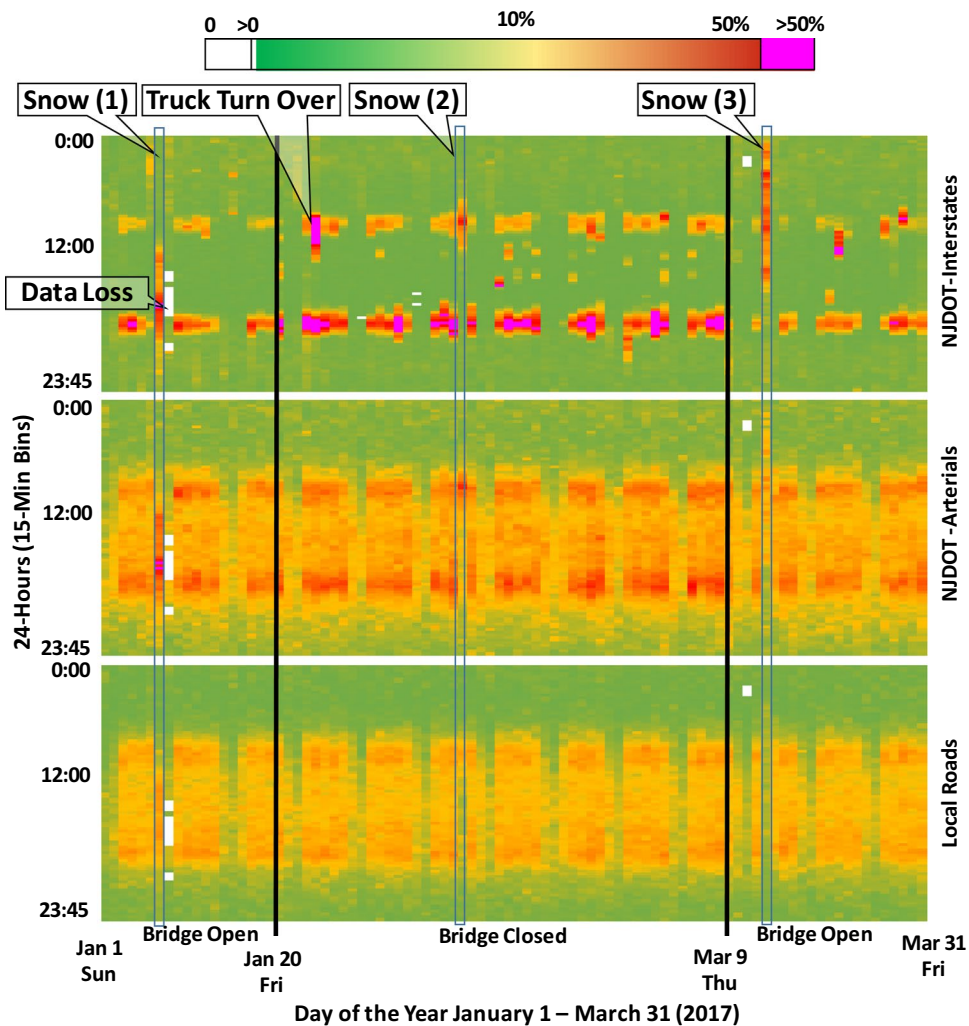
Most of the observations were noted to be recurring traffic patterns that are consistent across all counties. As would be expected, the snow days did show an impact across all the counties. One crash incident occurring on February 17, 2017 resulted in the closure of US-130 in both directions. US-130 runs parallel to both the New Jersey Turnpike and Interstate 295 and traverses each of the counties. The incident appeared to impact roadways in all three counties. The illustration demonstrated the county transportation systems' resiliency by its return to recurring congestion systems the following day. A similar observation is noted during the Saturday January 7, 2017 snow storm (Storm 1), where both the resiliency of the transportation system is shown, along with the resiliency of the data collection systems whose data were missing across the region immediately following the snow. Following the snow, the transportation system as well as the data collection returned to pre-storm conditions.

With respect to the start and end dates of the bridge closure event, it appears that Mercer County had an increase in MTT while the bridge, located in Burlington County,

was closed. Detours in the region had travelers directed to I-95/I-295 in Mercer County instead of the bridge. Figure 2 shows a change in the MTT coinciding with the bridge closure. Thus, the MTT measure clearly captures the impact of the I-276 bridge closure on Mercer County, as seen by the minimal impact on Camden and Burlington Counties. It also captures Mercer County's ability to recover from the detour after the bridge re-opened.

With Mercer County being identified as the most impacted county, the MTT data can be disaggregated to better observe the interdependency of the congestion on the interstate roadways versus the arterial as well as the local road. The NJDOT roadways were disaggregated into NJDOT-maintained arterials and interstates as shown in Fig. 3. An additional analysis of 615 TMCs representing roadways in Mercer County that are not maintained by NJDOT is also shown in Fig. 3. By disaggregating the roadways, it appears that the interstates incurred the brunt of the increase in MTT due to the bridge closure. However, the measures for arterials also show that they were impacted by the bridge closure. The measures for local roads

Fig. 3 MTT for Mercer, NJ (1019 TMCs)



show that they were not necessarily impacted by the I-276 bridge closure, at least not directly. One incident identified in Fig. 2 as a truck turn over on an I-95 on-ramp, had more of an observable impact when shown only on the interstate heat map, Fig. 3. It should be noted that Interstate 95 only traverses Mercer County, and the incident occurred in a relatively rural part of New Jersey.

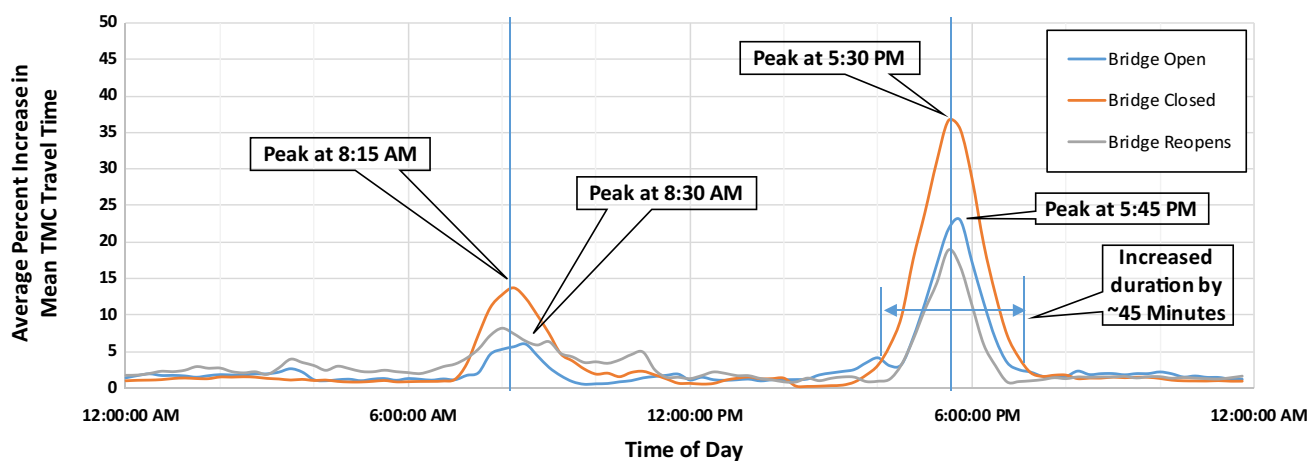
Average Mean Percent Change in TMC Travel Time Applied to Mercer County, NJ

The visualization in Figs. 2 and 3 provides an overall view of the changes in MTT for 15-min intervals over 90 days. To observe a generalized relationship of the impact the bridge closure had on Mercer County the average MTT is defined in Eq. 7.

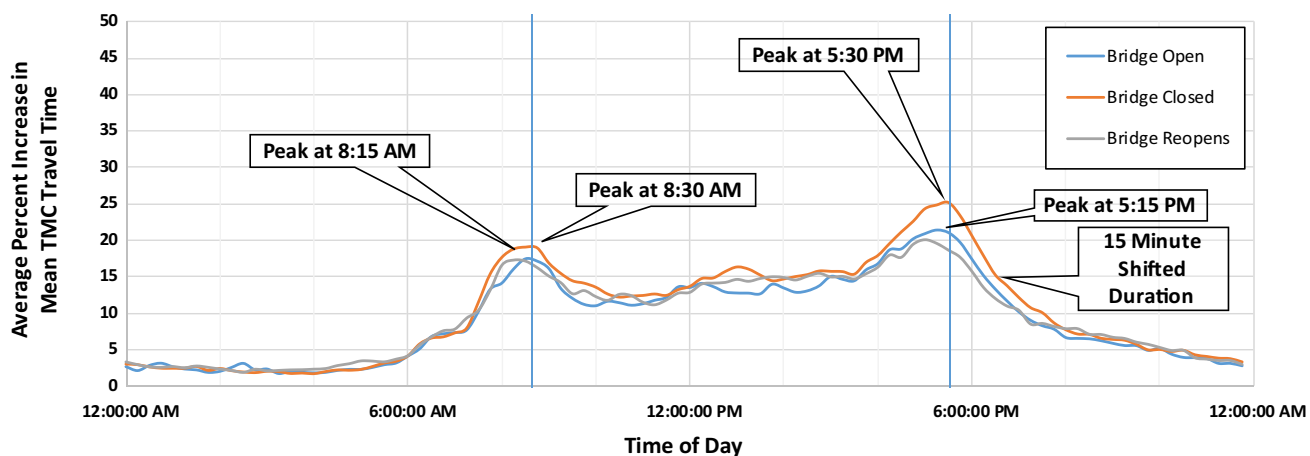
$$\overline{MTT}_{cj} = \frac{\sum MTT_{cj}}{D_t}, \tag{7}$$

where \overline{MTT}_{cj} is the average mean percent increase in TMC travel time (average MTT) for all TMCs in a county region, c , during a 15-min period, j divided by the number of days D , over the defined time period, t .

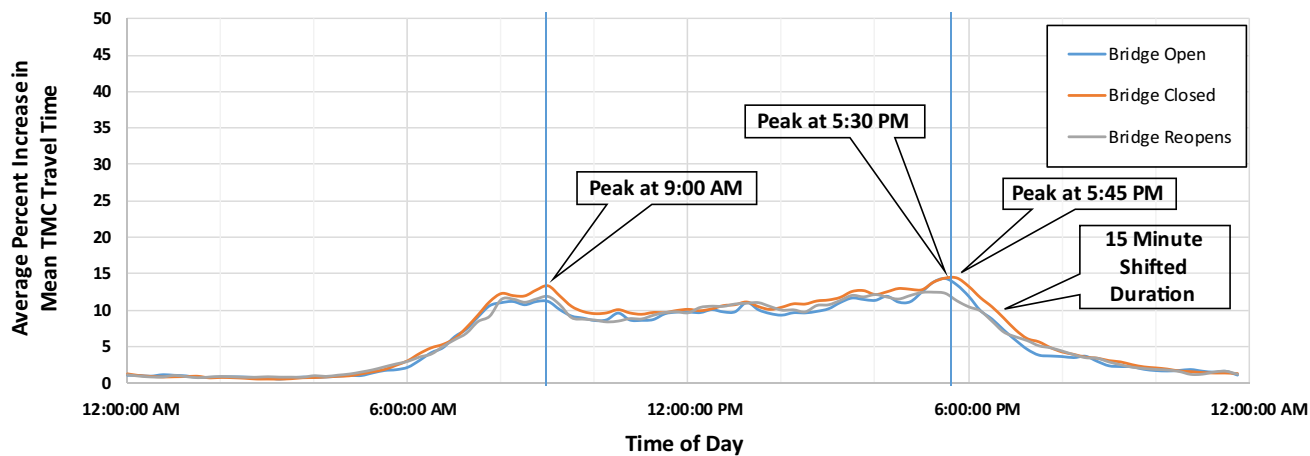
The time periods are 19 days between January 1, 2017 and January 20, 2017, 50 days between closing and opening of the bridge, and 21 days from the opening of the bridge to March 31, 2017. Although the day-to-day MTT was visually identified in Figs. 2 and 3, the graphical representations shown in Fig. 4 identify the collective impact on the interstates, arterials, and local roadways. From these graphs, the impact on the peak MTT is identified along with duration of the increased travel time due to the bridge closure. The graphs show that the interstates do see a major change in MTT, while the arterial has a minimal change, and the local roads do not show a change. The interstate average MTT decreased to a point where it was lower than the pre-bridge closure conditions in the PM Peak. These results might be enhanced by focusing on the



(a) NJDOT Maintained Interstates



(b) NJDOT Maintained Arterials



(c) Local Roadways

Fig. 4 Average MTT for Mercer, NJ (1019 TMCs)

micro-impact on the local roadways rather than the macro impact on the region.

Although both Camden and Burlington did not show any definitive change in MTT in Fig. 2, the average MTT in Fig. 5 yielded changes in the average MTT. While the bridge closure had an observable impact, increase in travel times, on Mercer County for Figs. 2, 3 and 4, Camden County reflected a decrease in average MTT in the PM Peak when the bride closed, and a subsequent increase in MTT in both the AM and PM peak travel times that exceeded the pre-closure MTT. Burlington County appeared to be unaffected by the bridge closure, but when the bridge re-opened the PM peak MTT increased. Further research will determine if these are statically significant changes and the reason for these fluctuations, but for this study what is to be understood is that there appears to be a cross county relationship to the bridge closure that is reflected in the MTT and average MTT.

To statistically evaluate the effect the I-276 bridge closure had on Mercer County’s transportation the maximum average percent increase in daily MTT was selected as the random variable. This value represents the greatest percent increase over the base travel time seen in each day between January 1, and March 31, 2017. This period includes data prior to the closure and after the reopening of the I-276 bridge. Figure 6 compares the Empirical Cumulative Distribution Functions (ECDF) for the maximum average percent increase in daily mean TMC travel time for the periods before the bridge closure and after reopening. The data sets used in the Fig. 3 were compared using a two-sample Kolmogrove–Smirnov (KS) test. The KS test was used to evaluate the null hypothesis of the data sets coming from the same continuous distribution at 95% confidence. For road types (interstate, arterial, and local), the null hypothesis was not rejected indicating that there is no significant difference between the maximum average percent increase in daily mean TMC travel time before and after the

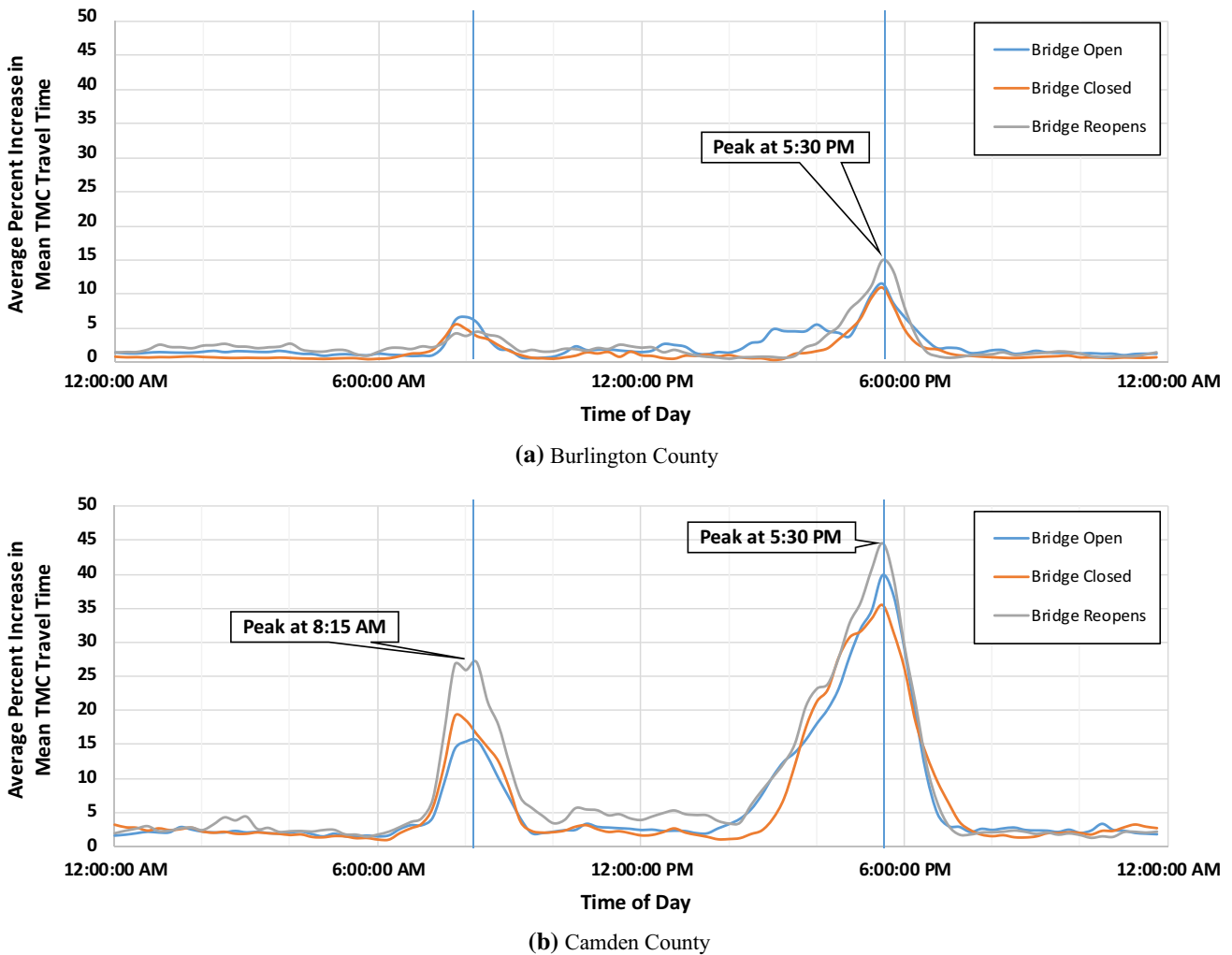


Fig. 5 Average MTT for NJDOT-Interstates

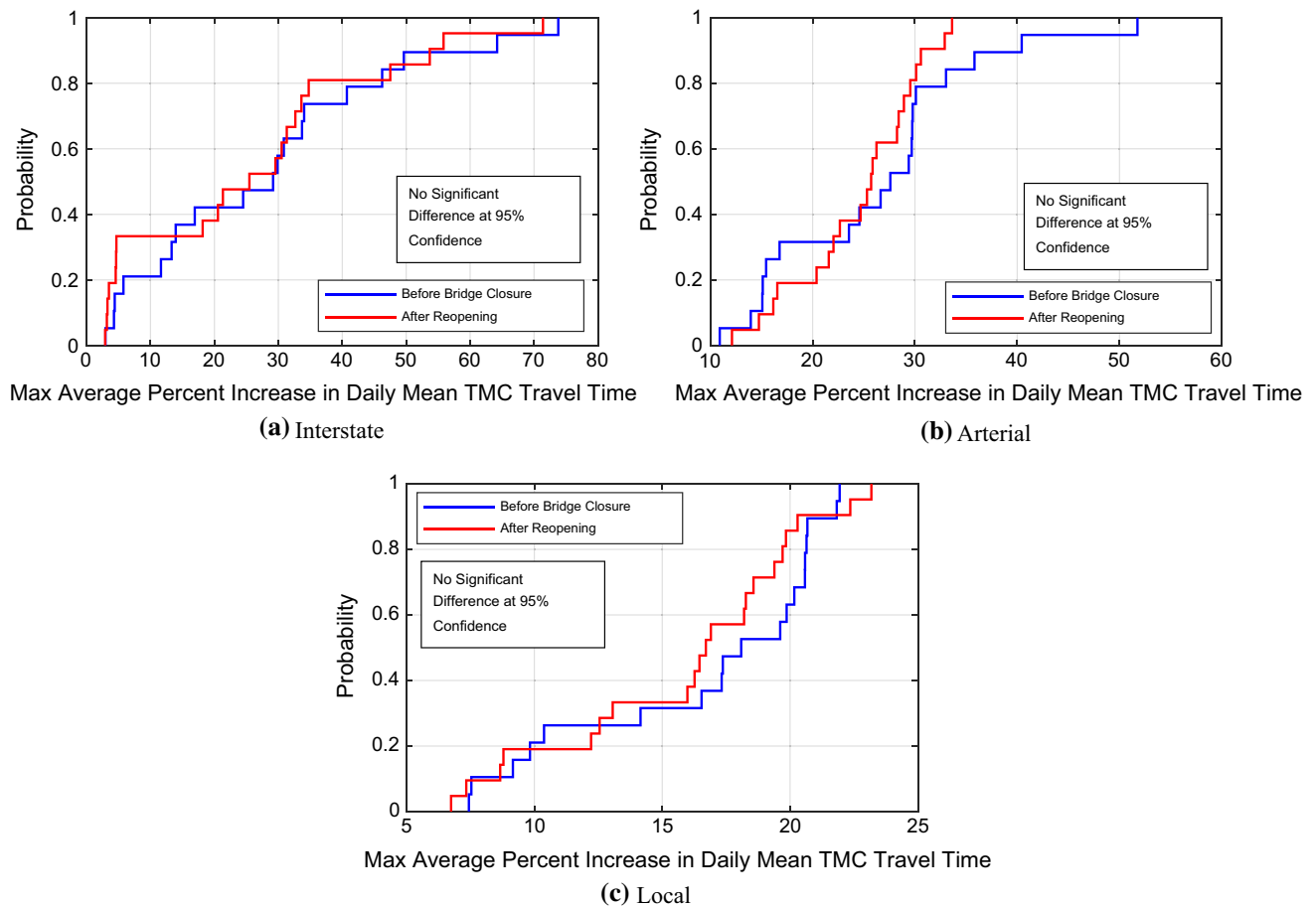


Fig. 6 Empirical cumulative distribution function of average daily maximum percent increase in MTT in Mercer County, NJ (before and after bridge closure)

bridge closure. This allowed this data, when the bridge was open, to be combined into a set representing the conditions when the bridge is open.

Figure 7 shows the ECDF plot for data sets representing the maximum average percent increase in daily mean TMC travel time with the bridge opened and closed. The KS test was performed in the same manner as previously described on these data sets. When comparing the bridge open and closed data, the null hypothesis was rejected for both interstate and arterial roadways. This indicates that the I-276 bridge closure had a statistically significant impact on the maximum average percent increase in daily mean TMC travel time for these road types. This difference was not seen on local roadways. These results support the observations made in Figs. 3 and 4.

Spatial Distribution of Average Mean Percent Increase in TMC Travel Time

To quantify the congestion derived from each of the TMCs, the average MTT in Eq. 7 was calculated for each TMC in Mercer County. The maps in Fig. 8, show the average MTT impacted TMCs within the counties before, during, and after the road closure. The bridge crossings from Pennsylvania into New Jersey at the US-1, I-295, and Calhoun Bridge appear to be the most impacted. A section of US-130 near the NJ Turnpike also appears to be impacted. This map also demonstrates how the MTT can be disaggregated to show where areas of high congestion

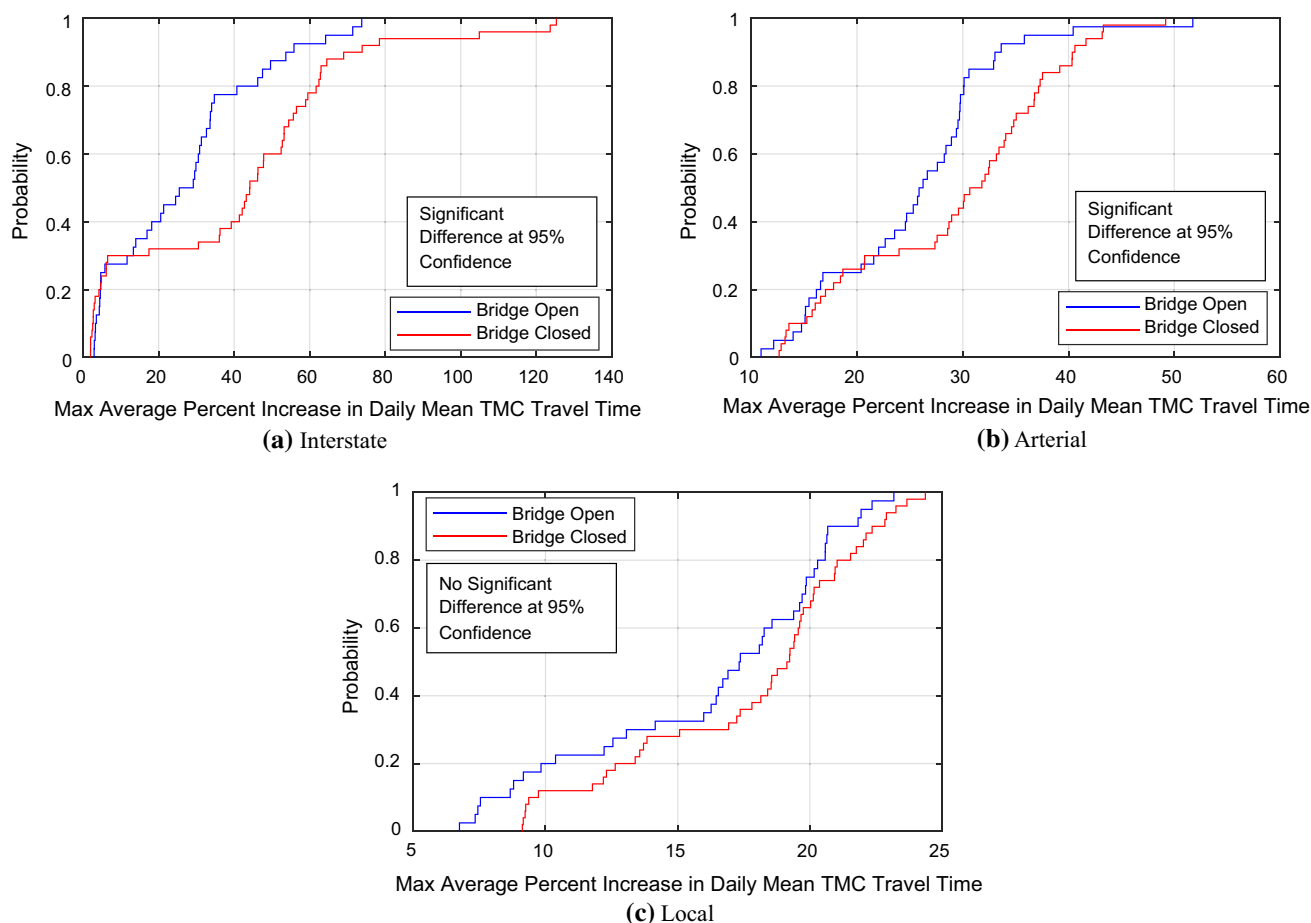


Fig. 7 Empirical cumulative distribution function of average daily maximum percent increase in MTT in Mercer County, NJ (before/after and during bridge closure)

are located in the region. This map can be adjusted to show the day-to-day, or minute-to-minute, changes to the network. Additional research will need to be conducted as the individual roadway impacts across Mercer County.

Conclusions

Commercially available big data from probe vehicles can be used to evaluate and to quantify the complex relationships and resiliency associated with the infrastructure failure within a regional roadway network. This research applied a scalable mean percent increase in TMC travel time (MTT) performance measure that quantifies change in base free flow travel time (BTT). This performance measure was used to visualize the complexities of the interdependent roadway networks within Mercer, Burlington, and Camden, counties of New Jersey, USA using a heat map visualization methodology. The MTT was specifically applied to 90 million probe vehicle speed data points to measure the changes, and eventual recovery, in regional travel time resulting from

the abrupt closing of the I-276 Bridge near Philadelphia, PA. The performance metric allowed a comparison of the relational impact among three counties before, during, and after the bridge closure. The research demonstrated that a graphical ‘heat map’ representation of the bridge closures can be derived directly from probe vehicle data. When the bridge was closed, there was a notable increase in MTT for Mercer County that returned to near pre-closure MTT once the bridge reopening. The visualized data illustrated the regional resiliency of Mercer County during the closure. A subsequent drill down of the data showed that the closure impacted the interstates as well as the arterial roadways, but had little impact on the local roadways.

To better illustrate the quantitative impact of the bridge closure on the roadways of three counties, the average mean increases in TMC travel time \overline{MTT} were computed. Although the ‘heat map’ representation of the bridge closure event showed no apparent impact in Burlington and Camden Counties, average MTT did show an impact. On the other hand, the results demonstrated that the bridge closure increased the MTT in Mercer County, which was confirmed

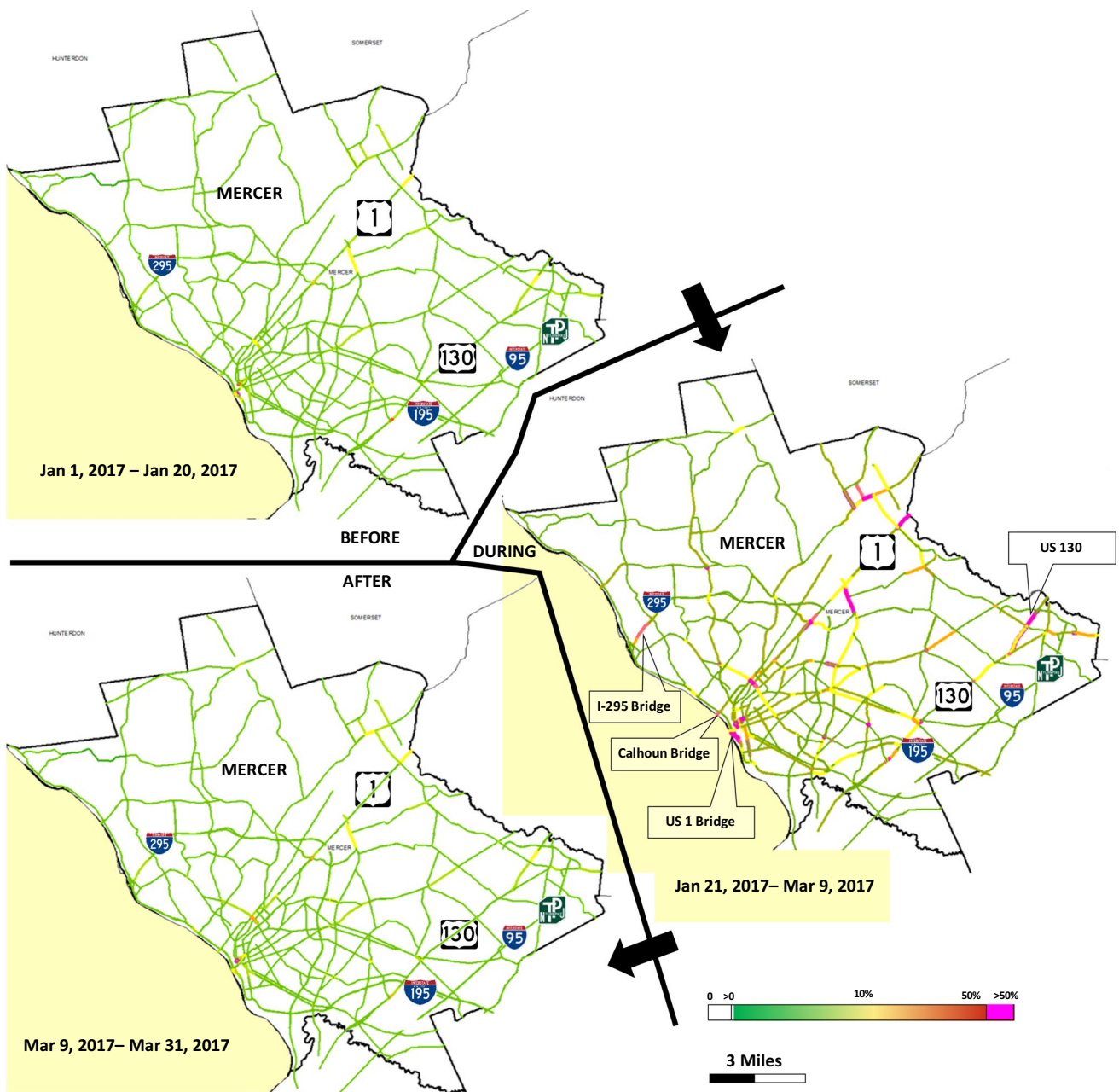


Fig. 8 Spatial distribution of average MTT for each TMC in Mercer County, NJ (1019 TMCs)

from the ‘heat maps’ but had a decrease in average MTT for Burlington County, where the I-276 Bridge is located. The average MTT was disaggregated for Mercer County to spatially identify the TMCs most impacted from the bridge closure. The map indicated that the three bridges in Mercer County to be the most impacted, with some additional impact seen along the interstate and some arterial routes. The ability to disaggregate MTT and average MTT demonstrates that probe data can be used to first identify an issue within a region, then quickly pinpoint where the issues might be occurring. Although this the research presented in this

paper explores only historic speed data, the methodologies presented can be applied to real-time speed data sets. Currently the authors are advancing this research towards developing real-time visualization tools.

As the probe vehicle data are becoming more reliable, its use in regional traffic management plans is becoming more prevalent. This increasing use of the data requires standards to be established for leveraging this data to produce ongoing monitoring of the transportation system at local, state, regional, and national levels. A significant challenge with respect to probe vehicle data is managing the bulkiness

of the data and developing innovative big data analytical methods. The methods used, and performance measures and visualization tools developed in this research address some of these challenges. Furthermore, the methods and metrics outlined in this research help determine the local and regional impact of incidents, weather events and the potential outcome of planned disruptions. By applying these methods on probe vehicle data in real time can potentially help improve the efficiency of managing regionally distributed traffic systems as network disruptions unfold. Further research can explore the need for determining data-driven regional boundaries, instead of arbitrary boundaries, which may inadvertently gerrymander congestion out of an agency's situational awareness. Ultimately, the ability to visualize interdependencies among and with a region's transportation network can help in the planning for temporary or permanent infrastructure investment.

Acknowledgements The contents of this paper 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. The speed data and segment information used in this report were obtained from INRIX Inc.

Author Contributions The authors confirm contribution to the paper as follows: study conception and design: TMB, MMV; data collection: TMB, RAG, AJB; analysis and interpretation of results: TMB, RAG, AJB, MMV; draft manuscript preparation: TMB, RAG, AJB, MMV. All authors reviewed the results and approved the final version of the manuscript.

References

- Argos G (2019) Pennsylvania-NJ bridge closed 7 weeks reopens ahead of schedule. <http://www.mcall.com/news/nationworld/pennsylvania/mc-pa-bridge-closed-to-open-03092017-20170309-story.html>. Accessed 19 Feb 2019
- Brennan TM, Venigalla M (2017) Incorporating speed data to analyze evacuation route resiliency. In: ITS World Congress; October 29–November 2, Montreal, Canada. Paper AM-SP0892
- Brennan TM, Remias SM, Mariani LJ (2015) Performance measures to characterize corridor travel time delay based on probe vehicle data. *Transp Res Board* 2526:39–50
- Brennan TM Jr, Venigalla MM, Hyde A, LaRegina A (2018a) Performance measures for characterizing regional congestion using aggregated multi-year probe vehicle data transportation research record. *J Transp Res Board*. <https://doi.org/10.1177/0361198118797190>
- Brennan TM Jr, Day CM, Volovski M (2018b) Ranking statistically similar highway travel corridors using speed data sets. *Infrastruct Asset Manag* 5(3):96–104. <https://doi.org/10.1680/jinam.17.00016>
- Brennan TM Jr, Gurriell RA, Bechtel A, Venigalla MM (2019) Performance metrics for visualizing interdependent regional traffic congestion using aggregated probe vehicle data. In: Compendium of papers, transportation research board 97th annual meeting
- Brown K (2019) Overturned garbage truck shuts I-195 onramp to N.J. Turnpike in Robbinsville. https://www.nj.com/mercer/index.ssf/2015/07/overturned_garbage_truck_shuts_i-195_onramp_to_nj.html. Accessed 19 Feb 2019
- California Department of Transportation (2011) Mobility Performance Report 2009
- Day CM, Brennan TM, Hainen AM, Remias SM, Bullock DM (2012) Roadway system assessment using bluetooth-based automatic vehicle identification travel time data. Purdue University, West Lafayette. <https://doi.org/10.5703/1288284314988>
- Few S (2009) Now you see it. Analytical Press, Oakland
- Haghani A, Hamdi M, Sadabadi KF (2009) I-95 Corridor coalition vehicle probe project: validation of Inrix data July–September 2008-Final Report. I-95 Corridor Coalition
- Hara Y, Kuwahara M (2015) Traffic Monitoring immediately after a major natural disaster as revealed by probe data—a case in Ishinomaki after the Great East Japan Earthquake. *Transp Res Part A Policy Pract* 75:1–15
- Highway Capacity Manual, sixth edition (2016) A guide for multimodal mobility analysis. Transportation Research Board, Washington, DC
- Lomax T, Shrank D, Eiselee B (2011) 2011 Urban mobility report powered by INRIX traffic data. The Texas A&M University System, Texas A&M Transportation Institute, College Station
- Lomax T, Shrank D, Eiselee B (2012) 2012 Annual urban mobility report. The Texas A&M University System, Texas A&M Transportation Institute, College Station
- Maryland Department of Transportation (2012) 2012 Maryland state highway mobility report
- Pack ML (2012) Wide-area, web-based mobility analysis using probe data. In: 2012 15th international IEEE conference on intelligent transportation systems. IEEE, pp 1682–1686
- Remias S, Brennan T, Grimmer G, Cox E, Horton D, Bullock D (2012) 2011 Indiana interstate mobility report—full version. West Lafayette, Indiana: Purdue University, Indiana Mobility Reports. Report No.: ISBN: 978-1-62260-209-4
- Remias SM, Brennan TM, Day CM, Summers HT, Horton DK, Cox ED, Bullock DM (2013) Spatially referenced probe data performance measures for infrastructure investment decision makers. Submitted to Transportation Research Board, Paper No. 14-1062
- Remias S, Brennan T, Day C, Summers H, Cox E, Horton D, Bullock D (2014) 2012 Indiana mobility report—full version. West Lafayette, Indiana: Purdue University, Indiana Mobility Reports; 2013. Report No.: ISBN: 978-1-62260-257-5
- Route 130 Shut Down In Cinnaminson After Car Strikes Pole. <https://philadelphia.cbslocal.com/2017/02/17/portion-of-route-130-shut-down-after-car-strikes-pole>. Accessed 20 Feb 2019
- Schrank D, Eiselee B, Lomax T, Bak J (2015) 2015 urban mobility scorecard
- Washington State Department of Transportation (2012) The 2012 Congestion Report

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.