Systemic evaluation of spatio-temporal variations in travel time reliability due to a toll road over time

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ABSTRACT
This paper evaluates the effectiveness of toll roads in reducing congestion and improving travel time reliability on streets within its vicinity, over time. The data, from the year 2013 to 2017, for the Triangle Expressway in the city of Raleigh, North Carolina was used in the systemic evaluation process. The spatial and temporal variations in the travel time distributions on the toll road, parallel route, and near-vicinity cross-streets (in a 2-mile buffer) were evaluated. The average travel time (ATT), the 95th percentile travel time (or planning time, PT), the buffer time (BT), and the buffer time index (BTI) were computed for each link by the day-of-the-week and the time-of-the-day. Though there was an improvement in travel time after the speed limit change in the year 2014, the travel time reliability got reduced on the Triangle Expressway. Over time, there was a gradual improvement in BT and BTI. The parallel route reliability decreased significantly over time, whereas the travel time reliability of cross-streets showed a consistent trend. The stabilization of travel time distributions and the reliability measures in the year 2017 indicate that further reduction in performance measures may not be expected in the next few years on the near-vicinity links.

1. Introduction
Rapid urbanization led by economic growth has intensified the urban travel demand in many cities worldwide. The acute growth in passenger cars overloading urban travel with problems of traffic congestion, high transportation costs, and traffic safety problems across the world. The findings published by the Texas Transportation Institute (TTI) revealed that congestion cost in the United States is growing at a far-reaching rate (Schrank et al., 2015). According to their findings, in the year 2014, traffic congestion incurred 6.9 billion hours of extra travel time and 3.1 billion gallons of extra fuel in the United States alone. Markedly, the above figures convert into approximately 160 USD billion during the year 2014, whereas the congestion costs were approximately 42 USD billion in the year 1982 and 114 USD billion in the year 2000 in the United States (Schrank et al., 2015). As far as the state of North Carolina is concerned, the congestion...
cost increased significantly in the last two decades. The Urban Mobility Report published by the TTI revealed a congestion cost of 1,015 USD million for the city of Charlotte, NC and 546 USD million for the city of Raleigh, NC in the year 2017, respectively (Schrank & Lomax, 2019).

The lack of funding for the infrastructure development and maintenance prompted researchers and transportation planners to think over improvement of urban and regional mobility beyond the application of traditional solutions such as constructing new highways and widening roads/adding lanes, which can be provided through planning the transportation system using smarter sustainable strategies and technological advancements. Toll roads, express toll lanes, light rail transit (LRT), commuter rail, intelligent transportation systems (ITS), etc., are example smarter sustainable strategies and technological advancements adopted by agencies for alleviating congestion and improving mobility in urban areas. As an example, the Triangle Expressway in the city of Raleigh is the first toll road that has been in operation since the year 2013, while Blue Line LRT in the city of Charlotte is the first LRT that has been in operation since the year 2007 in the state of North Carolina.

In the city of Raleigh, North Carolina, most commuters rely on the automobile to get to work. Almost 80% of workers drove alone and nearly 13% carpool. While considering the state North Carolina as a whole, 83% of the workers drove alone to work in the year 2007. This increased to 86% in the year 2017 (Robinson, 2019). It has become increasingly challenging to rely on constructing new highways or widening roads/adding new lanes to cater the needs of the growing travel demand. Therefore, many mid-sized urban areas in the United States have been exploring solutions such as toll roads, express toll lanes, and LRT to cater the travel demand, reduce congestion, and improve mobility.

Toll roads are fundamentally aimed at influencing the travel patterns and reducing the demand for travel on congested corridors, by segregating motorists based on the value of time, need for travel, and the significance of their trip. Motorists are free to decide whether to use the toll road or not based on if time saved is worth the cost or not. This could result in a reduction in congestion on express toll lanes/toll roads and general-purpose lanes, in particular, during peak hours of a day. The benefits associated with express toll lanes/toll roads depend on the time-of-the-day. Similarly, the investments in LRT or commuter rail have wide-ranging benefits (reduction in traffic volume, travel mode options, comfort, convenience, improvement in air quality, etc.).

This paper evaluates the effectiveness of toll roads in reducing congestion and improving travel time reliability on links within their vicinity, using data for the Triangle Expressway in the city of Raleigh, North Carolina for the years 2013 to 2017.

The purpose of this paper is to develop a systemic framework to evaluate the effect of toll roads on the region's traffic using travel time and travel time reliability measures, over space and time. In other words, comparing the travel time reliability measures over time at toll roads and other near-vicinity corridors will provide useful insights into the successful dimensions of large-scale transportation projects like express toll lanes/toll roads, LRT, etc., over years of its operation. Besides, comparing the travel time reliability measures for the years 2013 and 2014 with 2017 will provide useful insights pertaining to the long-term trends. The systemic travel time reliability-based performance evaluation methodology outlined in this research paper helps practitioners in comparing the
2. Literature review

Congestion pricing has received more attention in the field of urban traffic congestion mitigation related research and practices in recent years. It is a transportation demand management measure (Hensher & Puckett, 2007; De Palma & Lindsey, 2011; Wang et al., 2015). The decision to implement congestion pricing strategies are usually made using regional travel demand forecasting models and long-term transportation planning evaluations. The problems associated with such macro-level modeling are mainly related to steady state traffic conditions or demand-type of capacity-supply functions (Zheng et al., 2016). Some researchers have also discussed the anomalies associated with the forecasted traffic volume and the actual traffic volume on toll roads (Li & Hensher, 2010; Naess et al., 2006; Odeck & Skjeseth, 1995). Welde (2011) discussed the risk associated with the inaccurate forecast of traffic based on the Norwegian toll projects evaluation. As the successful dimensions of a toll road project are highly dependent on the results of the feasibility studies, it is important to evaluate the actual performance of toll roads over the years of the toll road operation.

One of the general measures of transportation project performance is the cost-benefit analysis (Chi et al., 2017; Van Wee & Rietveld, 2014). Monetary benefits of the toll road have also been reviewed by Oh et al. (2007). They discussed road pricing, revenue generation, and the cost associated with the toll road project. Chi et al. (2017) studied various methods of toll road evaluation based on research purpose and the item evaluated. A comprehensive list of previous research on the evaluation of toll road projects has also been summarized in their study.

Kalmanje and Kockelman (2009) studied the effect of the toll road on socio-economic and traffic characteristics of a region by considering toll roads in Texas. They have conducted a before-after toll road comparison of volume to capacity ratio (v/c), vehicle miles traveled (VMT), vehicle hours traveled (VHT), and the average speed in the study area. They concluded that the influence of toll roads mainly concentrated within a mile of a toll road.

The performance evaluation is critical to the success of long-term transportation projects, especially at the beginning of its operation. A comprehensive list of various performance measures is summarized in the National Highway Cooperative Research Program (NCHRP) report on ‘Evaluation and Performance Measurement of Congestion Pricing Projects’ (Perez et al., 2011). They identified measures based on traffic performance, public perception, facility users, system operations, transit, environment, economics, and land use. While looking into the traffic performance, they identified the level of service (LOS), speed/average speed, travel time, travel time savings, delay per wait time, etc., as the potential measures (Perez et al., 2011).

Travel time can be used as a benchmark to evaluate the performance of a toll road, as well as to compare with travel times of alternative routes to the destination (Perez et al., 2011). The operational performance of the arterial roads can be evaluated based on the travel time reliability indices (McLeod et al., 2012; Schrank & Lomax, 2002). The average travel time (ATT) can be considered as an indicator of the nominal level of congestion.
The planning time (PT), buffer time (BT), and the buffer time index (BTI) indicate the reliability of the transportation system. Goodin et al. (2013) proposed measures such as BTI and planning time index (PTI) for the performance evaluation of managed lanes. Pulugurtha et al. (2017) suggested the use of ATT and BT for quantifying the effect of transportation projects. The mathematical equations to compute ATT, PT, BT, and BTI are provided in the ‘Methodology’ section.

Presently, there is a research gap related to the performance evaluation of toll roads. There is no effective methodology for evaluating the performance of a toll road and its effect on near vicinity links based on travel time or travel time reliability indices. The short-term and long-term effects of toll roads are also not widely evaluated. Therefore, the main objective of this research is to develop a systemic framework to evaluate the effect of a toll road on region’s traffic using travel time and travel time reliability measures, over space (near vicinity links) and time (over the years of the toll road operation).

3. Methodology

The Triangle Expressway in Raleigh, NC, parallel route NC 55 and roads within its vicinity of two-miles (US 64, US 1, and NC 54) were considered as the study area for this research. The systemic evaluation process of this research is divided into the following steps.

(1) Study area profile
(2) Data collection
(3) Data processing a) Geographic Information Systems (GIS)-based link identification b) Travel time data processing using Microsoft Structured Query Language (SQL)
(4) Data evaluation a) Link-level travel time reliability i. Short-term evaluation (year-to-year comparison) ii. Long-term evaluation b) Corridor-level travel time distributions
(5) Testing the statistical significance of improvement

Each step is explained next in detail.

3.1. Study area profile

The Triangle Expressway was constructed as a new facility to reduce congestion on NC 55, the parallel route, in the city of Raleigh, North Carolina while improving access to the Research Triangle Park. The region is a major employment and business center in the city of Raleigh, North Carolina.

The Triangle Expressway is an 18.8-mile toll road that extends the partially complete ‘Outer Loop’ around the greater Raleigh, North Carolina area, from I 40 to NC 55 Bypass. The Triangle Expressway was constructed and opened for access in three phases. Phase 1 was extended from NC 147 south to meet NC 540, which at the time terminated right at NC 54. The next two segments, constructed as Phase 2 and Phase 3, cut through all the way down to NC 55 Bypass. The construction of all three segments began at the same
time, in August 2009. The tolling operation for the Triangle Expressway was started on 2 January 2013. Mathew et al. (2019) and Mathew and Pulugurtha (2019) outlined the phases of toll road construction and evaluated travel time measures on the parallel route and cross-streets during different phases of the Triangle Expressway construction.

Figure 1 shows the Triangle Expressway location in the city of Raleigh, North Carolina, United States. The toll rates were estimated \( = 0.15 \text{ USD per mile (0.15 USD per 1.6 km)} \) for vehicle owners with NC Quick Pass transponder, and estimated \( = 0.23 \text{ USD per mile (0.23 USD per 1.6 km)} \) for vehicle owners who pay the bill by mail, in the year 2013. With an average increase of 3.5% per year, the toll rates were estimated \( = 0.18 \text{ USD per mile (0.18 USD per 1.6 km)} \) for vehicle owners with NC Quick Pass transponder, and estimated \( = 0.27 \text{ USD per mile (0.27 USD per 1.6 km)} \) for vehicle owners who pay the bill by mail, in the year 2017 (North Carolina Turnpike Authority, 2017a).

It is envisioned that the spatial and temporal effects of toll roads can be effectively captured by analyzing travel time variations on the toll road and other near-vicinity corridors. It is assumed that the effect of toll roads would be mainly concentrated within 2-mile vicinity of the toll road. The study links were identified within this 2-mile vicinity. The selected study links are shown in Figure 2.

### 3.2. Data collection

The raw travel time data were gathered from the Regional Integrated Transportation Information System (RITIS) website (RITIS, 2018) at one-minute intervals. The data were collected from the probe vehicle network which contains more than hundreds of thousands of the global positioning system (GPS) enabled vehicles with advanced transmitting capabilities. In this research, the real-time traffic data (confidence score is 30) was considered for the evaluation. The raw travel time data contains data corresponding to the time-of-the-day, the day-of-the-week, the average speed, the travel time, and
the sample size. The data corresponding to each link (a small portion of a road with uniform characteristics) is coded with a unique identification code, a nine-digit Traffic Message Channel code (TMC-code). For convenience, a three-character ID was generated for each individual link in this research. The first character stands for the type of the road; T: toll road, P: parallel route, C: cross-street. The second character is a numeric starting from 1 which denotes the order of TMC-code in the direction of the traffic movement. Finally, the third character represents the direction of the traffic movement; N: Northbound, S: Southbound, E: Eastbound, and W: Westbound. For example, ‘T1S’ represents the first link or TMC on the toll road in the southbound direction. Finally,
travel time data were separately collected for the toll road, parallel route, and other near-vicinity corridor links for the years 2013 to 2017, at one-minute intervals.

3.3. **Data processing**

The data were processed in two sub-steps. They are discussed next.

3.3.1. **GIS-based link identification**

ArcGIS software (ESRI, 2018) was used to identify links on the toll road and near to the toll road vicinity. Geocoding was done using the start- and end-point coordinates, and the data were transferred to the scaled map of North Carolina road network obtained from the NCDOT. A buffer of 2-mile was generated along the Triangle Expressway, and the links within the 2-mile buffer were identified on the near-vicinity corridors (Figure 2). The three-character IDs corresponding to each selected link are labeled in Figure 2.

3.3.2. **Travel time data processing using Microsoft SQL**

Data corresponding to weekday and weekend traffic (7:00 AM – 8:00 AM, 12:00 PM – 1:00 PM, 5:00 PM – 6:00 PM, & 8:00 PM – 9:00 PM) were segregated using Microsoft SQL (Microsoft 2017) and RStudio package (RStudio Team, 2020).

The effect of recurrent congestion can be effectively quantified from the travel time reliability evaluation during the peak and off-peak hours. The peak hour delay associated with the travel corridor usually creates uncertainty to the motorists since they do not have a clear idea about the required time to reach the destination. Therefore, it is very important to capture the variability in travel times using travel time reliability measures. In this research, travel time reliability measures like ATT, PT, BT, and BTI were considered for the evaluation and computed for each link by the day-of-the-week and time-of-the-day. PT, BT, and BTI were computed using equations 1, 2, and 3.

\[
\text{Planning Time (PT)} = 95\text{th percentile travel time} \quad (1) \\
\text{Buffer Time (BT)} = \text{PT} – \text{ATT} \quad (2) \\
\text{Buffer Time Index (BTI)} = \frac{\text{BT}}{\text{ATT}} \quad (3)
\]

3.4. **Data evaluation**

The evaluation of the data was carried out separately for the toll road, parallel route, and near-vicinity cross-streets. Travel time performance measures for the identified links were computed for each year after the toll road operation. Initially, the evaluation was carried out at the link-level, as it effectively captures the variation in travel times for each link (disaggregate-level) under varying traffic conditions during different times of the day. The year-to-year changes in travel time reliability were evaluated to examine short-term effects, while the travel time reliability in the years 2013 and 2014 were compared with the travel time reliability in the year 2017 to evaluate long-term effects. The computation of the corridor travel time distributions followed this task.
3.5. **Testing the statistical significance of improvement**

The statistical significance of the change in travel time performance measures, over the years of Triangle Expressway operation, was evaluated using the one-tail paired t-test (Kimmel, 1957). The evaluation was performed at a 95% confidence level. The null hypothesis assumes that the actual mean difference in the travel time performance measure between the considered study years is zero. The alternative hypothesis assumes that the actual mean difference in the travel time performance measures between the considered study years is less than zero.

4. **Results from the travel time reliability evaluation**

Travel time reliability measures for the selected links of the toll road, the parallel route, and the cross-streets were computed for the years 2013, 2014, 2015, 2016, and 2017. The results from the short-term and long-term evaluations are presented in following subsections.

4.1. **Short-term evaluation**

The results from the evaluation of year-to-year changes in travel time reliability on the toll road, parallel route, and cross-streets are discussed in this subsection.

4.1.1. **Toll road**

The entire stretch of the Triangle Expressway, comprised of 34 links, was considered for the evaluation. As the Triangle Expressway became fully functional in January 2013, the base year was set as 2013. Further, travel time reliability measures such as ATT, PT, BT, and BTI were also computed for the years 2014, 2015, 2016, and 2017. The majority of the links on the toll road showed a trend of improvement in travel time reliability measures over the years of its operation though the NCDOT traffic volume interactive map reported an increase in traffic volume over time, along the entire stretch of the Triangle Expressway.

For each selected link, the ratio between the respective travel time performance measures for the year compared to the previous year was computed. For example, the ATT corresponding to the year 2014 would be written in terms of a ratio to the ATT during the year 2013. A ratio greater than one indicates a deterioration in travel time performance measure when compared with the previous year while a ratio less than one indicates an improvement in the travel time reliability measure when compared with the previous year. The results for the toll road for a typical weekday morning peak hour are summarized in Table 1. Only selected links are included in Table 1. The cells with a value greater than 1.0 indicate the deterioration in performance measure after each year of the toll road operation.

For example, for link number T5S, ATT was 0.24 minutes in the year 2015. It increased by 4% in the year 2016 (ratio of after by before is 1.04 in the year 2016). Similarly, PT was 0.27 minutes in the year 2015 and decreased to 0.26 minutes in the year 2016 (ratio of after by before is 0.96 in the year 2016). The estimated BT is 0.01 and 0.03
for the years 2015 and 2016, which indicates a 66.7% decrease in BT in the year 2016 (ratio of after by before is 0.33 in the year 2016).

The travel time performance measure has improved on the majority of the links on the toll road from 7:00 AM to 8:00 AM on a weekday, a typical morning peak hour for work trips. The improvement is more consistent if the ratio of travel time reliability measures along the Triangle Expressway over the years are observed. However, while considering ATT and PT, there exists evidence of a reduction in the year 2014. This trend was observed on all the selected links. To find the reason behind such a decline in travel time during the year 2014, a scatter plot was generated using the entire travel time data (Figure 3).

From Figure 3, there is a change in travel time pattern in the year 2014 compared to the year 2013. As a cross-check, it was observed that there was an increase in the speed limit from 60 miles/hour (96.6 km/h) to 70 miles/hour (112.7 km/h) on the Triangle Expressway (from March 2014). The change in the speed limit on the Triangle Expressway decreased the travel time, whereas BT and BTI increased during the same period (difference between ATT and PT is higher). The BT and BTI are measures of trip reliability that indicate the extra time needed to be on time for 95% of the trips. Also, these measures allow the motorist to estimate extra time (in terms of time or percentage) that the trip may take under the prevailing traffic condition.

Some unusual trends or discrepancies are noted in Figure 3. For example, in the case of T10N, a few one-minute interval samples with travel time = ~1.2 minutes and speed ranging from 45 mph (72.4 km/h) to 55 mph (88.5 km/h) were observed during the year 2014. They only account for ~0.03% of total samples during the year 2014. Moreover, the PT is 0.97 minutes for this link. Such one-minute interval samples could be the result of

![Table 1. Short-term Evaluation of Travel Time Reliability on the Toll Road – Results.](image)

| Link     | Length (Miles) | Ratio of after by before ATT | Ratio of after by before PT | Ratio of after by before BT | Ratio of after by before BTI |
|----------|----------------|------------------------------|----------------------------|-----------------------------|-----------------------------|
| T5S      | 0.28           | 0.87                         | 0.96                       | 1.04                        | 1.00                        |
| T6S      | 1.17           | 0.82                         | 0.98                       | 1.00                        | 0.89                        |
| T7S      | 1.05           | 0.83                         | 0.98                       | 1.01                        | 0.89                        |
| T10N     | 0.97           | 0.79                         | 0.96                       | 1.00                        | 0.85                        |
| T11 N    | 1.05           | 0.77                         | 0.98                       | 1.00                        | 0.84                        |
| T12 N    | 0.44           | 0.84                         | 0.97                       | 1.03                        | 1.02                        |

Note 1: 1 - Ratio of the year 2014 measure to the year 2013 measure; 2 - Ratio of the year 2015 measure to the year 2014 measure; 3 - Ratio of the year 2016 measure to the year 2015 measure, 4 - Ratio of the year 2017 measure to the year 2016 measure.

Note 2: 1 mile = 1.61 kilometers.

![Table 2. Annual average daily traffic (AADT) estimates – toll road links.](image)

| Link     | Annual average daily traffic |
|----------|------------------------------|
| T25/T15 N | 2013  | 2014  | 2015  | 2016  | 2017  |
| T45/T13 N | 7,600 | 10,000 | 13,000 | -     | 15,000 |
| T75/T9N   | 13,000 | 18,000 | 23,000 | 27,000 | 31,000 |
| T115/T3N   | 9,500 | 15,000 | 20,000 | 24,000 | 27,000 |
| T135/T3N   | 9,700 | 15,000 | 20,000 | 22,000 | 24,000 |
| T155/T1N   | 7,200 | 11,000 | 13,000 | 16,000 | 17,000 |
Figure 3. Travel time variation – selected toll road links.
non-recurring events such as crashes, mechanical breakdown of vehicles, and inclement weather conditions. A few one-minute interval samples could also be attributed to peak hour congested conditions or some drivers driving slowly in spite of the increase in the speed limit, but were able to adjust their speeds by the year 2015.

The gap in the figures, between the years 2014 and 2015, is due to the missing data for 30 days (12 December 2014 to 12 January 2015), for all the selected links on the Triangle Expressway.

The high variations in travel times during the year 2014 compared to the year 2015 can also be observed in Figure 3. The high variations in travel times resulted in an increase of BT and BTI on the Triangle Expressway. Similar trends in travel times and related measures were observed for the years 2016 and 2017.

To examine the influence of traffic volumes on travel times over the years of operation, available count-based annual average daily traffic (AADT) estimates were gathered for toll road links and are summarized in Table 2. The AADT estimates are bi-directional. More than a 90% increase in the available AADT estimates was observed on toll road links over the years of operation. For example, in the case of T2S/T15 N, the AADT increased by almost 100% from the year 2013 to the year 2017. The increase in the AADT

Table 3. Short-term Evaluation of Travel Time Reliability on the Parallel Route – Results.

| Link | Length (Miles) | Ratio of after by before (ATT) | Ratio of after by before (PT) | Ratio of after by before (BT) | Ratio of after by before (BTI) |
|------|----------------|--------------------------------|-------------------------------|-------------------------------|-------------------------------|
|      |                | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| P3S  | 1.45           | 1.19 | 1.04 | 1.11 | 1.03 | 1.40 | 1.16 | 1.24 | 0.96 | 3.23 | 1.53 | 1.52 | 0.84 | 2.72 | 1.47 | 1.38 | 0.82 |
| P4S  | 2.26           | 1.17 | 0.93 | 1.04 | 1.03 | 1.27 | 0.94 | 1.06 | 1.10 | 2.00 | 1.01 | 1.17 | 1.35 | 1.70 | 1.08 | 1.13 | 1.31 |
| P5S  | 1.86           | 1.10 | 0.96 | 1.03 | 0.98 | 1.25 | 0.92 | 1.18 | 0.92 | 3.26 | 0.76 | 2.02 | 0.72 | 2.96 | 0.79 | 1.96 | 0.74 |
| P6S  | 0.82           | 1.15 | 1.00 | 1.03 | 0.95 | 1.35 | 1.04 | 0.97 | 1.00 | 2.97 | 1.15 | 0.80 | 1.16 | 2.58 | 1.15 | 0.77 | 1.21 |
| P7S  | 1.02           | 1.09 | 1.03 | 1.04 | 1.05 | 1.16 | 1.13 | 1.05 | 1.11 | 1.51 | 1.51 | 1.06 | 1.23 | 1.38 | 1.47 | 1.02 | 1.17 |
| P8S  | 0.78           | 1.07 | 1.05 | 1.17 | 1.00 | 1.07 | 1.22 | 1.35 | 1.00 | 1.08 | 1.98 | 1.77 | 1.00 | 1.01 | 1.89 | 1.51 | 1.00 |
| P9S  | 1.18           | 1.14 | 1.06 | 1.03 | 1.04 | 1.26 | 1.09 | 1.11 | 1.05 | -    | 1.39 | 1.09 | -    | 1.20 | 1.35 | 1.05 |
| P10S | 1.40           | 1.04 | 0.96 | 1.03 | 1.04 | 1.12 | 0.97 | 1.09 | 1.03 | 1.66 | 1.00 | 1.35 | 1.01 | 1.60 | 1.04 | 1.31 | 0.97 |
| P1N  | 0.76           | 1.04 | 1.05 | 1.06 | 1.03 | 1.15 | 1.15 | 1.12 | 1.12 | 1.93 | 2.17 | 1.36 | 1.26 | 1.85 | 2.08 | 1.29 | 1.22 |
| P2N  | 1.37           | 1.00 | 1.09 | 0.91 | 1.00 | 1.00 | 1.08 | 1.00 | 1.00 | 0.85 | 1.08 | 1.18 | 1.00 | 0.78 | 0.99 | 1.29 |
| P3N  | 1.18           | 1.18 | 1.02 | 0.96 | 0.96 | 1.33 | 1.06 | 1.00 | 0.90 | 2.15 | 1.17 | 1.12 | 0.76 | 1.82 | 1.15 | 1.17 | 0.79 |
| P4N  | 0.78           | 1.10 | 1.06 | 1.01 | 0.98 | 1.14 | 1.12 | 1.00 | 1.04 | 1.36 | 1.37 | 0.98 | 1.25 | 1.24 | 1.29 | 0.97 | 1.27 |
| P5N  | 1.02           | 1.14 | 1.07 | 1.10 | 1.12 | 1.30 | 1.18 | 1.09 | 1.24 | 2.48 | 1.56 | 1.08 | 1.52 | 2.17 | 1.46 | 0.98 | 1.35 |

Note 1: 1- Ratio of the year 2014 measure to the year 2013 measure; 2- Ratio of the year 2015 measure to the year 2014 measure; 3-Ratio of the year 2016 measure to the year 2015 measure, 4-Ratio of the year 2017 measure to the year 2016 measure.

Note 2: 1 mile = 1.61 kilometers.

Table 4. Annual average daily traffic (AADT) estimates – parallel route links.

| Link/year | 2013 | 2015 | 2017 |
|-----------|------|------|------|
| P1S/P11 N | 16,000 | 18,000 | 18,000 |
| P3S/P9N  | 25,000 | 26,000 | - |
| P4S/P8N  | 26,000 | 27,000 | 24,000 |
| P5S/P7N  | 26,000 | 28,000 | 23,000 |
| P6S/P6N  | 27,000 | 29,000 | 26,000 |
| P7S/P5N  | 28,000 | 27,000 | 26,000 |
| P8S/P4N  | 18,000 | 19,000 | 18,000 |
| P9S/P3N  | 27,000 | 31,000 | 27,000 |
| P10S/P2N | 43,000 | -    | 45,000 |
estimates on the toll road links is also supported by the increase in the AADT estimates on the near-vicinity cross-street links, entry ramps, and exit ramps.

4.1.2. Parallel route and cross-streets
According to the reports from the North Carolina Turnpike Authority (NCTA), the Triangle Expressway construction was preliminarily intended to relieve congestion on NC 55 (parallel route), while improving access to the Research Triangle Park by reducing travel times for motorists residing to the south and east of the region (North Carolina Turnpike Authority, 2017b). Therefore, a systemic evaluation of travel time variations on the parallel route, over time, is a logical necessity to comment on the outcome of this large-scale transportation project. Based on the link-level evaluation, results are not in favor of what was envisioned. The results from the link-level travel time reliability evaluation corresponding to a typical weekday peak hour (7:00 AM – 8:00 AM, Wednesday) are summarized in Table 3.

The majority of the links showed an apparent deterioration in ATT, PT, BT, and BTI over each year of its operation. As BT and BTI can depict the actual effect of the toll road on each selected link within the vicinity of the toll road, this is not a good trend and needs evaluation using the traffic volume.

To examine the influence of traffic volumes on travel times over the years of operation, the available count-based AADT estimates were gathered for the parallel route links and are summarized in Table 4. An increase in the AADT estimates was observed on the parallel route links from the year 2013 to the year 2015. However, a decrease or no change in the AADT estimates was observed on the parallel route links from the year 2015 to the year 2017.

The parcel-level land use data along the parallel route (land use change over the years) and near-vicinity cross-streets showed it as a residential zone with many major trip attractions. The land use and developments can be considered as a reason behind such a change in travel time reliability over time on the parallel route links. The reduction in AADT estimates over time can be considered as a good indicator as some of the existing traffic seem to be attracted to the more reliable toll road.

A similar evaluation was performed for the major cross-streets, US 64, NC 54 and US 1, for the selected years. Trends observed are similar along the cross-street links. Also, comparison of the AADT estimates in the 2-mile vicinity substantiated the findings from the evaluation of the toll road and parallel route links.

Table 5. Long-term Evaluation of Travel Time Reliability on the Toll Road – Results.

| Link | Length (Miles) | Measure in the year 2013 | Measure in the year 2014 | Ratio of the measure in the year 2017 to the measure in the year 2014 |
|------|----------------|--------------------------|--------------------------|---------------------------------------------------------------------|
|      | ATT PT BT BTI  | ATT PT BT BTI            | ATT PT BT BTI            | ATT PT BT BTI                                                       |
| T5S  | 0.28 0.29 0.32 0.04 14.29 0.25 0.34 0.09 36 | 1.00 0.76 0.11 0.11 |  |
| T6S  | 1.17 1.25 1.41 0.24 20.51 1.02 1.25 0.23 22.55 0.98 0.85 0.26 0.27 |  |
| T7S  | 1.05 1.11 1.26 0.21 20.00 0.92 1.12 0.2 21.74 | 0.99 0.85 0.20 0.20 |  |
| T10N | 0.97 1.04 1.14 0.17 17.53 0.82 0.97 0.15 18.29 0.99 0.88 0.27 0.27 |  |
| T11N | 1.05 1.14 1.26 0.21 20.00 0.88 1.06 0.18 20.45 0.98 0.86 0.28 0.28 |  |
| T12N | 0.44 0.45 0.51 0.07 15.91 0.38 0.52 0.14 36.84 0.97 0.75 0.14 0.15 |  |

Note: 1: 1 mile = 1.61 kilometers.
4.2. **Long-term evaluation**

The results from the evaluation of long-term changes on the toll road, parallel route, and cross-streets are discussed in this subsection.

4.2.1. **Toll road**

The long-term effect of toll roads on region’s traffic was assessed by computing and comparing the travel time reliability measures for the year 2017 (fifth-year of toll road operation) with 2013 (first-year of toll road operation) and 2014 (second year of toll road operation). The results from the evaluation performed for the toll road links for a typical weekday morning peak hour are summarized in Table 5. From Table 5, all the selected links on the toll road showed a trend of improvement in travel time reliability measures in the year 2017 compared to the year 2013 and 2014. For example, in the case of TSS, PT was 0.34 minutes in the year 2014 and it reduced to 0.26 minutes (a 24% reduction) in the year 2017.

4.2.2. **Parallel route and cross-streets**

The results from the link-level travel time reliability evaluation corresponding to a typical weekday peak hour for the parallel route are summarized in Table 6.

From Table 6, majority of the links on the parallel route showed a deterioration of travel time reliability in the year 2017 compared to the year 2014.

A similar evaluation was performed for the cross-streets, US 64, NC 54 and US 1, for the year 2017 and compared with the years 2013 and 2014. The results indicated a deterioration in travel time reliability measures on most of the cross-street links during the fifth-year after opening the toll road for complete service.

The goals of a large-scale transportation project like toll road is to improve mobility and reduce congestion on roads within its vicinity. However, such an improvement may be seen after a few years of operation (for example, after 4 or 5 years). From the long-term evaluation, there exists a change in travel time reliability over time compared to the first-year (2013) and the second-year (2014) of the toll road operation. However, the short-

| Link | Length | Measure in the year 2013 | Measure in the year 2014 | Ratio of the measure in the year 2017 to the measure in the year 2014 |
|------|--------|-------------------------|-------------------------|---------------------------------------------------------------------|
|      | (Miles)| ATT PT BT BTI           | ATT PT BT BTI           |                                                                                     |
| P3S  | 1.45   | 1.86 2.07 0.21 11.42    | 2.21 2.89 0.68 31.03    | 1.18 1.37 1.97 1.67                                                                 |
| P4S  | 2.26   | 2.8   3.16 0.36 12.66    | 3.29 4.00 0.71 21.52    | 0.99 1.10 1.58 1.60                                                                 |
| P5S  | 1.86   | 2.31 2.48 0.17 7.46      | 2.54 3.10 0.56 22.11    | 0.98 1.00 1.11 1.14                                                                 |
| P6S  | 0.82   | 1.11 1.25 0.14 12.46     | 1.28 1.69 0.41 32.12    | 0.98 1.00 1.06 1.08                                                                 |
| P7S  | 1.02   | 1.76 2.12 0.36 20.27     | 1.92 2.46 0.54 28.01    | 1.13 1.31 1.98 1.75                                                                 |
| P8S  | 0.78   | 1.28 1.57 0.29 22.2      | 1.37 1.68 0.31 22.36    | 1.23 1.65 3.51 2.84                                                                 |
| P9S  | 1.18   | 2.24 2.45 0.21 9.31      | 2.54 3.09 0.55 21.42    | 1.13 1.28 1.93 1.70                                                                 |
| P10S | 1.4    | 1.94 2.22 0.28 14.24     | 2.02 2.48 0.46 22.76    | 1.04 1.10 1.37 1.32                                                                 |
| P11N | 0.76   | 1.26 1.43 0.17 13.31     | 1.32 1.64 0.32 24.61    | 1.14 1.65 3.71 3.26                                                                 |
| P2N  | 1.37   | 3.88 6.3 2.42 62.24      | 3.89 6.30 2.41 61.96    | 1.08 1.08 1.08 1.00                                                                 |
| P3N  | 1.18   | 2.49 2.95 0.46 18.43     | 2.94 3.93 0.99 33.59    | 0.94 0.95 0.99 1.06                                                                 |
| P4N  | 0.78   | 1.24 1.47 0.23 18.9      | 1.36 1.68 0.32 23.38    | 1.05 1.17 1.66 1.58                                                                 |
| P5N  | 1.02   | 1.55 1.75 0.2 13.18      | 1.77 2.27 0.5 28.56     | 1.32 1.59 2.54 1.93                                                                 |

Note 1: Cells with a value greater than 1.0 indicate deterioration in travel time reliability.

Note 2: 1 mile = 1.61 kilometers.
term evaluation (year-to-year comparison) showed that the change in travel time reliability from the year 2014 to the year 2017 is marginal.

5. Results from corridor-level travel time distributions

The outcomes from the link-level evaluation indicate a trend of improvement on the majority of the selected links on the toll road and trend of deterioration on near-vicinity links (parallel route and cross-streets). Further, to quantify the overall improvement in travel time performance measure, a corridor-level evaluation, separately for the toll road, parallel route, and cross-streets, was performed.

5.1. Corridor-level evaluation of the toll road

To quantify the overall effect of the toll road on travel time reliability measures, cumulative frequency diagrams were generated at an aggregate level. Data normalization was carried out by dividing the travel time with the length of each link. The cumulative distribution of per mile travel times for the Triangle Expressway are summarized in Figure 4.

From Figure 4, there exists a wide disparity in the cumulative distribution of the year 2013 travel times compared to other years. The change in the speed limit could be the main reason behind such a significant shift in travel time distribution from the reference year 2013.

Figure 4 also shows that nearly 68% of the one-minute interval samples during the year 2013 are ~1 minute/mile (nearly free-flow condition; speed limit = 60 mph) on weekday/weekend morning and evening peak hours. Likewise, a nearly similar percentage of the samples are less than or equal to 0.86 minutes/mile (nearly free-flow condition; speed limit = 70 mph) on weekday/weekend morning and evening peak hours during the years 2014, 2015, 2016, and 2017. The distribution of samples seems to be fairly consistent and relatively equal during the years 2015, 2016, and 2017 compared to the year 2014. This could be attributed to drivers getting adjusted from the lower speed limit to the higher speed limit in the year 2014.

The AADT estimates are the lowest during the year 2013, followed by the year 2014 on the toll road links. The increase in traffic volume was highest from the year 2013 to the year 2015 when compared to from the year 2015 to the year 2017. The variations in travel times are relatively high in the year 2013, followed by the year 2014, due to low traffic volumes (could also influence the number of observed samples). Contrarily, the variations in travel times are relatively low during the years 2015, 2016, and 2017. This seems to be evident from the cumulative distribution plots for each year. Overall, the travel time distributions for the year 2015, 2016, and 2017 were observed to be very similar, no significant change in travel times, which indicate a stabilization of travel time distributions, over time on the Triangle Expressway.

Further, to check the statistical significance of such a change in travel time performance measures (ATT, PT, BT, and BTI), one-tail paired t-test was performed at a 95% confidence level. The null hypothesis is ‘H0: Travel time reliability measure remained the same after each year of operation (for example, BT 2014 – BT 2013 is equal to 0)’. The alternative hypothesis is ‘H1: Travel time reliability measure reduced after each year of operation (for example, BT 2014 – BT 2013 is less than 0). The one-
Tail paired t-test results for the toll road are shown in Table 7. For example, on a typical weekday morning peak hour, there is a statistically significant improvement in the ATT on the toll road links in the year 2014 compared to the year 2013 (p-value < 0.05; null hypothesis: ATT measure remained the same in the year 2014 compared to the year 2013 is rejected, Alternative hypothesis: ATT reduced in the year 2014 compared to the year 2013).

There exists a statistically significant improvement in ATT and PT during the year 2014. On the contrary, BT and BTI showed a significant deterioration during the same time period. Overall, the statistical analysis showed an improvement in travel time.
Table 7. Paired t-test Results.

| Time period | ATT 1–2 | 2–3 | 3–4 | 4–5 | PT 1–2 | 2–3 | 3–4 | 4–5 | BT 1–2 | 2–3 | 3–4 | 4–5 | BTI 1–2 | 2–3 | 3–4 | 4–5 |
|-------------|--------|------|------|------|--------|------|------|------|--------|------|------|------|--------|------|------|------|
| 7:00 a.m. – 8:00 a.m. Weekday | <0.01 | 0.09 | <0.01 | 0.38 | <0.01 | 0.01 | <0.01 | 0.39 | <0.01 | 0.03 | <0.01 | 0.29 | <0.01 | 0.01 | 0.01 | 0.17 |
| 12:00 p.m. – 1:00 p.m. Weekday | <0.01 | 0.16 | 0.01 | 0.19 | <0.01 | 0.31 | <0.01 | 0.26 | <0.01 | 0.39 | <0.01 | 0.31 | <0.01 | 0.32 | <0.01 | 0.17 |
| 5:00 p.m. – 6:00 p.m. Weekday | <0.01 | 0.07 | 0.09 | 0.44 | <0.01 | 0.03 | <0.01 | 0.22 | <0.01 | 0.01 | 0.02 | 0.07 | <0.01 | 0.02 | 0.05 |
| 8:00 p.m. – 9:00 p.m. Weekday | <0.01 | 0.47 | 0.17 | 0.42 | <0.01 | 0.17 | <0.01 | 0.45 | <0.01 | 0.08 | <0.01 | 0.47 | <0.01 | 0.04 | 0.46 |
| 7:00 a.m. – 8:00 a.m. Weekend | <0.01 | 0.34 | <0.01 | 0.20 | <0.01 | 0.12 | <0.01 | 0.42 | <0.01 | 0.46 | <0.01 | 0.31 | <0.01 | 0.47 | <0.34 |
| 12:00 p.m. – 1:00 p.m. Weekend | <0.01 | 0.06 | <0.01 | 0.05 | <0.01 | 0.05 | <0.01 | 0.14 | <0.01 | 0.01 | 0.30 | 0.41 | <0.01 | 0.04 | 0.46 |
| 5:00 p.m. – 6:00 p.m. Weekend | <0.01 | 0.06 | <0.01 | 0.05 | <0.01 | 0.05 | <0.01 | 0.14 | <0.01 | 0.01 | 0.30 | 0.41 | <0.01 | 0.04 | 0.46 |
| 8:00 p.m. – 9:00 p.m. Weekend | <0.01 | 0.01 | 0.07 | 0.37 | <0.01 | 0.01 | <0.01 | 0.21 | <0.01 | 0.01 | 0.15 | <0.01 | 0.01 | 0.01 | 0.20 |

Note: 1–2: 2013–2014; 2–3: 2014–2015; 3–4: 2015–2016; 4–5: 2016–2017
reliability over time. It is likely that the higher capacity of the Triangle Expressway (6-lane divided road) is capable of coping with higher traffic volume than the present volume.

5.2. **Corridor-level evaluation for parallel route and cross-streets**

The cumulative frequency diagrams for the parallel route and cross-streets provide useful indications of the overall increase in travel time and travel time reliability measures over time. On the parallel route, Figure 5, the travel time increased over time. Also, such a trend is clearer during the peak hours, 7:00 AM – 8:00 AM and 5:00 PM to 6:00 PM, on typical weekdays. Specifically, an overall shift is observed every year. The Research Triangle Park is one of the dominant locations for employment in the study region. Therefore, NC 55 can also be considered as a competing route to the Triangle Expressway, as it also provides access to the Research Triangle Park. As residences are predominant within the proximal area of NC 55, the peak hour demand for driving is one major factor behind the increase in travel time.

To understand the statistical significance of the trend mentioned earlier, one-tail paired t-test was performed, and the results are summarized in Table 7. The paired t-test results also show a similar trend of increase in travel time reliability measures, with statistical significance (at a 95% confidence level) in the year 2013 and the year 2014. The trend follows the same pattern until the year 2017. The travel time reliability reached a balanced state in the year 2017.

A similar evaluation was performed for the cross-streets (US 64, NC 54, and US 1). The results obtained are summarized in Figure 6. It is observed that the travel time distributions follow a similar trend of increase on cross-street links, after each year of operation of the Triangle Expressway. Also, the trend became stable during the year 2016 and the year 2017.

The travel time reliability measures showed an apparent deterioration in the year 2014 compared to the year 2013. Further, the change was not significant on the cross-street links. Other than a substantial increase in travel time reliability measures reported in the year 2016 compared to the year 2015, there is no significant change in travel time reliability on the major cross-street links.

The traffic and travel times on the cross-streets (arterial roads) are influenced by traffic signal controls, pedestrian crossings, conflicting traffic from other cross-streets, the presence of access points to various land use developments, etc. There exists a higher fluctuation in travel times on all the cross-street links. Therefore, the shape of the cumulative distribution curve is attributed to the general traffic characteristics on the selected cross-street links. The one-tail paired t-test results for cross-streets are also shown in Table 7.

The weekend traffic is generally different from the weekday traffic due to the change in the pattern of trips. Also, various spatial and temporal factors may influence the travel pattern. For example, the rapidly growing study area has many residential communities, institutions, and other major business attractions. These land use characteristics influence the trip patterns and travel time on the study links by day-of-the-week and time-of-the-day (specifically, during the peak hours when compared to the off-peak hours). In this research, the distribution of travel times (shown in Figures 4, 5, and 6) follow
a similar drift on the weekday and weekend over the year, in most evaluation scenarios. Moreover, as evident from Table 7, the one-tail paired t-test results also showed similar findings corresponding to the weekday and weekend test outcomes.

Figure 5. Cumulative distribution of normalized travel times on the parallel route.
Kalmanje and Kockelman (2009) examined the effect of toll roads on regions traffic and concluded that the congestion reduction is concentrated within a mile buffer. From this study, the impact of the toll road on near vicinity traffic is different for links which are near to the toll road compared to the links which are farther from the toll road. The

Figure 6. Cumulative distribution of travel times on cross-street links.

6. Discussion

Kalmanje and Kockelman (2009) examined the effect of toll roads on regions traffic and concluded that the congestion reduction is concentrated within a mile buffer. From this study, the impact of the toll road on near vicinity traffic is different for links which are near to the toll road compared to the links which are farther from the toll road. The
variation in travel time or change in travel time reliability on the cross-street links which are located near the toll road is minimal over time. However, there is more deterioration in travel time reliability over time on links which are farther from the toll road.

Li and Hensher (2010) examined traffic forecasting errors and factors influencing these errors in Australian toll projects. The errors in the initial years are high with the maximum error being −35.18% in the first year of operation. However, as the years of operations increased, a gradual decrease in these errors was observed. The model results from their research indicate that high values of errors in the forecast are associated with the presence of more toll lanes, static toll pricing strategy, and cash payment alternative, especially on higher toll road lengths. Their findings indicate that the predicted benefits associated with the toll road may be different over years of its operation.

Mathew et al. (2019) evaluated the efficiency of toll roads in reducing travel time and improving travel time reliability on the links adjacent to the toll road during different phases of toll road construction and after opening it for complete service. A statistically significant improvement in travel time reliability measures within the vicinity of the toll road after opening the toll road for complete service was observed. The travel time reliability measures such as BT and BTI for the parallel route (NC 55) decreased (improved) after each phase of the toll road operation. Similarly, the before-after comparison of traffic volume showed a notable reduction on the parallel route. However, from this research, there is an increase in travel time on the parallel route and cross-street links in the study area over time. Also, the BT and BTI deteriorated on the parallel route over time.

The AADT estimates increased on the toll road links over the years of operation. There was an increase in the AADT estimates over time on the cross-street links (especially, the entry and exit ramps to the toll road). However, the change in the AADT on parallel route links is not consistent over time. There was a marginal increase in the AADT estimates in the year 2015 compared to the year 2013, and a marginal reduction in the AADT estimates in the year 2017 compared to the year 2015, for most of the parallel route links with available data. Also, a notable decrease in AADT was observed on most of the parallel route links in the year 2013 when compared to before opening the toll road for complete service. This substantiates the shift of traffic from the parallel route to the toll road over time.

The Triangle Expressway is in a region with three cities: Chapel Hill, Durham, and Raleigh. There are several institutions, numerous tech companies and enterprises in the region. Recent population estimates from the American Community Survey indicated a 13% increase in population in the region from the year 2010 to the year 2018 (United States Census Bureau, 2018). Moreover, the parcel-level land use data for the study area indicated a growth in residential and commercial areas within the vicinity of the Triangle Expressway during the evaluation period. These can be considered as a plausible explanation for the general growth in traffic volume and change in travel time reliability over time on the selected roads in the study area.

Overall, the reduction in the AADT estimates over time on the parallel route and a significant increase in the AADT estimates on the toll road can be considered a good indicator as some of the existing traffic and new traffic seems to be attracted to the more reliable toll road. Also, there was stabilization in travel times on the toll road and the parallel route in the year 2016 and 2017. Further, the change in travel time reliability is
found to be less in the year 2017 compared to the year 2016 on all the study links. This indicates that further reduction in travel time reliability may not be seen, in the next few years, on the toll road and near vicinity links.

7. Conclusions

This paper presents an evaluation of travel time reliability of a toll road and its effectiveness in reducing traffic congestion and improving travel time reliability on other roads within its vicinity. The travel time reliability of the toll road was analyzed for different years of its operation, starting from the year 2013 to the year 2017. The ATT, the 95th percentile travel time (or PT), BT, and BTI were computed for each link, by the day-of-the-week and the time-of-the-day. Specifically, data corresponding to typical peak hours of weekday traffic and weekend traffic was identified for the evaluation.

The findings indicate that the Triangle Expressway showed a positive trend in reliability over the years of its operation. A sudden change in travel time reliability was observed in the year 2014, due to the change in speed limit on the toll road. Moreover, there is a significant increase in AADT reported on the toll road during the evaluation period. The distinguishing capability of expressways in managing higher traffic volume is evident from the evaluation.

The Triangle Expressway project purpose was to mitigate congestion on the parallel route (NC 55). It is one of the major roads that provide access to the rapidly growing Triangle Research Park area. The increase in traffic volume on the Triangle Expressway can be considered as a positive result, as the majority of new traffic is attracted to the more reliable toll road. The stabilization of travel time distributions and the reliability measures in the year 2017 are good indicators, suggesting that further reduction in performance measures may not be seen in the next few years on the toll road and near vicinity links. It also indicates that benefits from the implementation of a large-scale transportation projects may be evident four to five years after its completion and being in operation.

The effect of large-scale transportation projects varies spatially and temporally. The cross-streets analyzed in this research substantiated the geospatial and temporal variation of travel times over the years of the toll road operation. The findings from the evaluation of travel time distributions and the statistical tests revealed no change in travel time reliability measures on the considered cross-street links over time (other than the major change in the year 2014 compared to the year 2013).

The long-term evaluation of the effect of toll roads on near vicinity traffic was carried out by comparing travel time reliability measures for the year 2013, 2014 and 2017 for the toll road, parallel route, and the cross-streets. The toll road links showed a trend of improvement in travel time reliability in the year 2017. However, the parallel street and cross street links showed a clear trend of deterioration in travel time reliability in the year 2017 compared to the years 2013 and 2014.

The travel time distribution and the reliability evaluation corresponding to the toll road, parallel route, and the cross-streets for the weekday and weekend (the majority of the selected time intervals) depicted a similar pattern, over different years of toll road operation. In a general context, the weekend trip pattern is significantly different from the weekday trip pattern due to the personal and household trip characteristics. In that
scenario, considering individual characteristics, household characteristics, type of vehicle used, and trip purpose may provide vital insights into the weekday-weekend travel time comparison. Conducting an in-depth analysis of land-use, socio-economic, and traffic volume (by time-of-the-day and day-of-the-week) related aspects of the project corridor and near vicinity links would further improve the study applicability. Also, actual tolling or pricing related aspects of the Triangle Expressway are not included in this research.

A systemic framework for the evaluation of large-scale transportation projects like toll roads, over years, of its operation, is proposed in this research. Considering the change in land use patterns and traffic volumes after the implementation of toll road may provide a better picture pertaining to long-term transportation project outcomes and its magnitude.

Historically, the emphasis has been on building new roads, adding new lanes, etc., in mid-sized urban areas in the United States. Many mid-sized urban areas have been exploring toll roads and public transit systems such as LRT in recent years to reduce congestion and meet mobility needs. With the availability of continuous travel time data, the effectiveness of these types of large-scale projects in meeting the goals can be evaluated. Undoubtedly, the exact magnitudes of the effects in terms of travel time or travel time reliability may differ from place to place and by the type of project. However, the methodological framework adopted in this research can be applied for all such types of project evaluations.

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