9-2019

How Effective are Toll Roads in Improving Operational Performance?

Sonu Mathew

Srinivas S. Pulugurtha

Project 1804 | September 2019

SJSU SAN JOSÉ STATE UNIVERSITY

MTI MINETA TRANSPORTATION INSTITUTE

How Effective are Toll Roads in Improving Operational Performance?

Sonu Mathew
Srinivas S. Pulugurtha, PhD

MINETA TRANSPORTATION INSTITUTE
LEAD UNIVERSITY OF
Mineta Consortium for Transportation Mobility

Founded in 1991, the Mineta Transportation Institute (MTI), an organized research and training unit in partnership with the Lucas College and Graduate School of Business at San José State University (SJSU), increases mobility for all by improving the safety, efficiency, accessibility, and convenience of our nation's transportation system. Through research, education, workforce development, and technology transfer, we help create a connected world. MTI leads the four-university Mineta Consortium for Transportation Mobility, a Tier 1 University Transportation Center funded by the U.S. Department of Transportation's Office of the Assistant Secretary for Research and Technology (OST-R), the California Department of Transportation (Caltrans), and by private grants and donations.

MTI's transportation policy work is centered on three primary responsibilities:

Research

MTI works to provide policy-oriented research for all levels of government and the private sector to foster the development of optimum surface transportation systems. Research areas include: bicycle and pedestrian issues; financing public and private sector transportation improvements; intermodal connectivity and integration; safety and security of transportation systems; sustainability of transportation systems; transportation / land use / environment; and transportation planning and policy development. Certified Research Associates conduct the research. Certification requires an advanced degree, generally a Ph.D., a record of academic publications, and professional references. Research projects culminate in a peer-reviewed publication, available on TransWeb, the MTI website (http://transweb.sjsu.edu).

Education

The Institute supports education programs for students seeking a career in the development and operation of surface transportation systems. MTI, through San José State University, offers an AACSB-accredited Master of Science in Transportation Management and graduate certificates in Transportation Management, Transportation Security, and High-Speed Rail Management that serve to prepare the nation's transportation managers for the 21st century. With the active assistance of the California Department of Transportation (Caltrans), MTI delivers its classes over a state-of-the-art videoconference network throughout the state of California and via webcasting beyond, allowing working transportation professionals to pursue an advanced degree regardless of their location. To meet the needs of employers seeking a diverse workforce, MTI's education program promotes enrollment to under-represented groups.

Information and Technology Transfer

MTI utilizes a diverse array of dissemination methods and media to ensure research results reach those responsible for managing change. These methods include publication, seminars, workshops, websites, social media, webinars, and other technology transfer mechanisms. Additionally, MTI promotes the availability of completed research to professional organizations and journals and works to integrate the research findings into the graduate education program. MTI's extensive collection of transportation- related publications is integrated into San José State University's world-class Martin Luther King, Jr. Library.

REPORT 19-28

HOW EFFECTIVE ARE TOLL ROADS IN IMPROVING OPERATIONAL PERFORMANCE?

Sonu Mathew
Srinivas S. Pulugurtha, PhD

September 2019

A publication of

Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José, CA 95192-0219

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. 19-28	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle How Effective are Toll Roads in Improving Operational Performance?		**5. Report Date** September 2019 **6. Performing Organization Code**
7. Authors Sonu Mathew, https://orcid.org/0000-0003-2263-2749 Srinivas S. Pulugurtha, https://orcid.org/0000-0001-7392-7227		**8. Performing Organization Report** CA-MTI-1804
9. Performing Organization Name and Address Mineta Transportation Institute College of Business San José State University San José, CA 95192-0219		**10. Work Unit No.** **11. Contract or Grant No.** 69A3551747127
12. Sponsoring Agency Name and Address U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology University Transportation Centers Program 1200 New Jersey Avenue, SE Washington, DC 20590		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplemental Notes		

16. Abstract

The main focus of this research is to develop a systematic analytical framework and evaluate the effect of a toll road on region's traffic using travel time and travel time reliability measures. The travel time data for the Triangle Expressway in Raleigh, North Carolina, United States was employed for the assessment process. The spatial and temporal variations in the travel time distributions on the toll road, parallel alternate route, and near-vicinity cross-streets were analyzed using various travel time reliability measures. The results indicate that the Triangle Expressway showed a positive trend in reliability over the years of its operation. The parallel route reliability decreased significantly during the analysis period, whereas the travel time reliability of cross-streets showed a consistent trend. The stabilization of travel time distributions and the reliability measures over different years of toll road operation are good indicators, suggesting that further reduction in performance measures may not be seen on the near vicinity corridors. The findings from link-level and corridor-level analysis may help with transportation system management, assessing the influence of travel demand patterns, and evaluating the effect of planned implementation of similar projects.

17. Key Words Toll roads, Travel time, Travel demand management, Transportation system management	**18. Distribution Statement** No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161		
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 55	**22. Price**

Form DOT F 1700.7 (8-72)

Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu

100319

ACKNOWLEDGMENTS

The authors sincerely thank the staff of the North Carolina Department of Transportation (NCDOT) and the Regional Integrated Transportation Information System (RITIS) website for providing the data required for this research.

The authors thank Editing Press, for editorial services, as well as MTI staff, including Executive Director Karen Philbrick, PhD; Deputy Executive Director Hilary Nixon, PhD; Graphic Designer Alverina Eka Weinardy; and Executive Administrative Assistant Jill Carter.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Over the past two decades, there has been increased attention towards the management of congestion by means of pricing strategies such as the use of toll roads. This is in contrast with earlier efforts, which were mainly focused on capacity enhancement measures. Toll project design and pricing strategies are generally developed using conventional four-step modeling processes and other long-term transportation planning assessments. The outcomes of such priori modeling, however, may be entirely different from what is observed in the real world. In other words, the long-term impact of such transportation projects is very difficult to capture from the conventional traffic forecasting models and assessments. Therefore, empirical research is warranted to analyze and understand how well these facilities may operate, over time, through various performance evaluation benchmarks. This research is, therefore, carried out to evaluate the efficacy of toll roads in reducing travel time and improving travel time reliability on links (segments of a road which are defined based on the unique identification code named Traffic message channel, TMC) within its vicinity, using data for the Triangle Expressway in Raleigh, NC, USA. The objective of this research is to develop a systematic analytical framework to evaluate the effect of toll roads on region's traffic using measures of travel time and travel time reliability, over space and time.

Travel time-based analysis over space quantifies how the effectiveness changes as we get further from the toll road. Likewise, travel time-based performance evaluation over time evaluates how the effectiveness varies over time since initiation of the toll in the Triangle Expressway. The raw data for this research, which contains travel time, average speed, and reference speed, for each link, all categorized by time-of-the-day and by day-of-the-week, was obtained from the Regional Integrated Transportation Information System (RITIS) database. The data corresponding to each link is coded with a single unique identification code, referred to as TMC ID.

The data processing was carried out at two levels. At the primary level, geospatially-based TMC/link identification was carried out, followed at the secondary level by the development of travel time reliability indices. ArcGIS was used to identify the links in the toll road vicinity.

The variables of interest were average travel time (ATT), 95th percentile travel time (PT), buffer time (BT), and the buffer time index (BTI). Each was computed for each link and classified by day-of-the-week and by time-of-the-day. Data was analyzed only for typical peak hours of weekday traffic and weekend traffic (7:00 a.m.–8:00 a.m., 12:00 p.m.–1:00 p.m., 5:00 p.m.–6:00 p.m., and 8:00 p.m.–9:00 p.m.). The travel time reliability of the toll road, parallel alternate road, and cross-street were all studied both at the individual-link level and at the corridor level, for different phases of toll road construction and operation (Phase 1, Phase 2 , and Phase 3), and then over the years of toll operation post-construction (2013, 2014, 2015, 2016, and 2017). The link-level analysis gives a clear picture of the travel time variations at the level of individual segments of road, while corridor-level analysis quantifies the overall effect of the toll road on travel time reliability measures for the selected corridors. Finally, the statistical significance of the change in travel time performance measures was evaluated using a one-tail paired t-test; the analysis was performed at a 95% confidence level.

During different phases of the Triangle Expressway's operation, for links on the parallel alternate road (NC 55), the measures of travel time reliability (BT and BTI) improved after each phase of the operation. As BT and BTI indicate the extra time for a trip needed to account for unexpected delays, the downwards trend can be considered as a positive effect of the Triangle Expressway on the region's traffic. There was also a notable decrease in traffic volumes along the parallel alternate road during and following the construction of the toll road. This result is in accord with the Triangle Expressway project's purpose, which was to mitigate congestion on the parallel alternate road (NC 55).

The study results indicate a positive trend in reliability over the years of operation of the Triangle Expressway. Along the Triangle Expressway, even though there was a decrease in travel time immediately after the speed limit change in 2014, an increase in travel time reliability measures was observed at the same time. Along the parallel alternate road, NC 55, travel time reliability reduced significantly over the whole analysis period, while for the cross-streets, travel time reliability remained more or less the same. The stabilization of travel time distributions and the improvement in reliability measures by 2017 are good indicators, suggesting that further worsening in performance measures may not be expected on the toll road or in the near-vicinity corridors.

The Triangle Expressway is a six-lane divided road. From the analysis, it is evident that the high capacity of the Triangle Expressway makes it capable of coping with higher traffic volumes than its present volume at the time of this writing. The nearby Research Triangle Park is one of the dominant locations for employment in the study region. Therefore, the parallel alternate road (NC 55) also competes and provides access to the Research Triangle Park in addition to the Triangle Expressway. Growing land use developments around the parallel alternate road can also be a factor for the increase in the peak hour travel demand.

The effects of large-scale transportation projects can vary spatially and temporally. The analysis in this research of cross-streets at varying distances from the Expressway, and during different years of the toll road operation, substantiated the geospatial and temporal influence on the effects of the toll on travel times.

Traffic volume analysis based on the AADT data obtained from the NCDOT showed a significant increase in traffic volume through the Triangle Expressway over the whole study period. It is plausible that most of the new traffic was attracted by the toll road, in which case the toll project can be viewed as a success.

Overall, this research demonstrates the value of quantitatively assessing large-scale transportation projects like toll roads over the years of their operation, and further such research is recommended. The study results and methodology illustrated in this research provide useful insights into the practices and policies currently used for the evaluation of large-scale transportation projects. Considering the change in land use patterns and traffic volumes after the implementation of the toll road may provide a better picture of the intensity and outcomes of long-term transportation projects.

I. INTRODUCTION

Population growth, technological advancements, increase in average life expectancy, the availability of newer and more fuel-efficient vehicles, and the growth of urban sprawl, have led to a meteoric rise in travel demand over the past two decades. Findings published by the Texas Transportation Institute (TTI), in 2015, have revealed that congestion cost in the United States is growing at an accelerating rate. They estimated that, in 2014, traffic congestion incurred 6.9 billion hours of extra travel time and 3.1 billion gallons of extra wasted fuel in the United States alone. Notably, the above figures correspond to approximately $160 billion in congestion costs during 2014, whereas the congestion costs were approximately $42 billion in 1982 and $114 billion in 2000 (values in constant 2014 dollars) in the United States.[1]

There is little government funding available for new roads or for increasing the capacity of existing roads due to budget constraints and the need to maintain already-existing and aging road infrastructure. An emerging trend is to construct toll roads or express lanes, through public-private partnerships (PPP), to effectively manage the road infrastructure and reduce congestion on urban roads. These strategies are aimed at reducing the demand for transportation on congested corridors, by segregating motorists based on their valuing of time and on their need for travel.

The Triangle Expressway was constructed by the North Carolina Turnpike Authority (NCTA), a unit of the North Carolina Department of Transportation (NCDOT), in order to improve commuter mobility, accessibility, and connectivity to western Wake County and the Research Triangle, while reducing congestion on the existing north-south routes that serve the Triangle Region, primarily NC 55 and NC 54. The project's cost was just over $1 billion and is the single largest transportation infrastructure project in North Carolina history.[2]

The Triangle Expressway was constructed and opened for access in three phases. The first phase, which connected NC 540 between NC 55 and NC 54, opened in December 2011, with toll collection beginning on January 3, 2012. The second and third phases of construction of the Triangle Expressway were completed in August 2012 and December 2012, respectively; they connected NC 540 between NC 54 and NC 55 Bypass in Holly Springs, with the tolling operations for the second and third phases beginning on August 2, 2012 and January 2, 2013, respectively. Overall, the Triangle Expressway is an 18-mile long toll road in the Triangle Region. A map of the Triangle Expressway is shown in Figure 1.

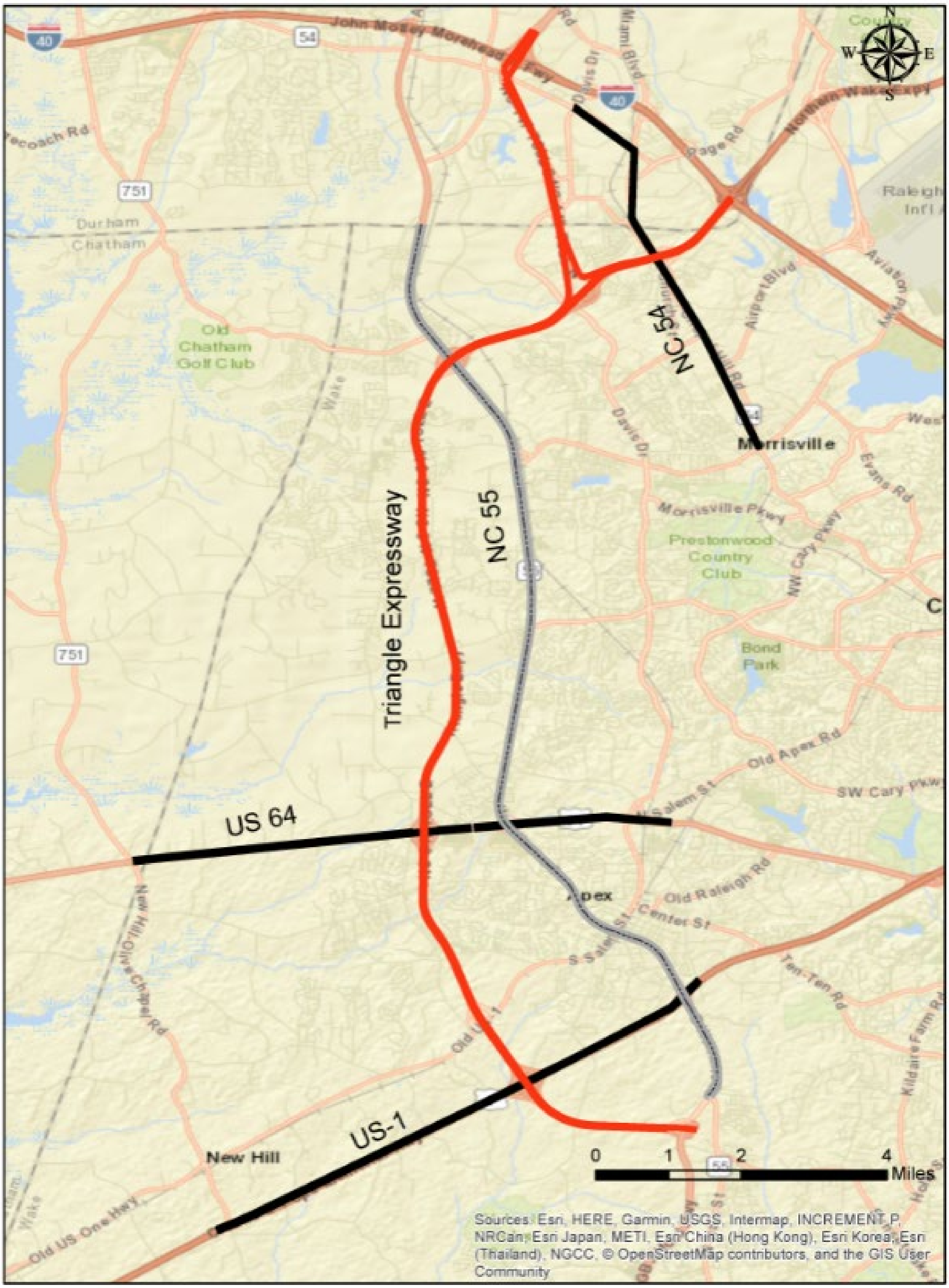

Figure 1. Triangle Expressway Map View

Decisions to implement transportation projects such as toll roads and express lanes are generally made through the use of regional travel demand forecasting models and long-range transportation planning. It is also important, however, to empirically monitor and evaluate the effectiveness of toll roads in mitigating traffic congestion and in improving travel times, after the implementation. In this research, the effect of the toll road on travel time reliability of the links adjacent to the toll road was analyzed for distinct periods: before construction; during Phase 1 construction; during Phase 2 construction; and, after opening the toll road for complete service, over different years of toll road operation.

PROBLEM STATEMENT

At present, there are gaps in research related to the performance evaluation of toll roads. There is no effective or widely accepted methodology for evaluating the performance, based on travel time or travel-time reliability indices, of a toll road and roads in its vicinity. Furthermore, the majority of the research which has been done in the past has neglected the spatial and temporal effects of large-scale transportation projects on the region's traffic and system performance. Given this background context, the present research aims to evaluate the efficacy of toll roads in reducing travel time and improving travel time reliability on links within its vicinity, using data for the Triangle Expressway in Raleigh, NC, USA.

The purpose of this research is to develop a systematic analytical 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, and then to use that framework to evaluate the Triangle Expressway. The travel time reliability-based performance evaluation methodology outlined in this research report will be a useful tool for practitioners to use in comparing the performance or efficiency of other toll roads/managed lane facilities over years of their operation.

RESEARCH OBJECTIVES

The objectives of this research are:

1. to collect available data on travel times and traffic counts, and to evaluate the effectiveness of a toll road in reducing travel time and improving travel time reliability on links within its vicinity; and

2. to examine the spatial and temporal dependence of the effects of the toll road within its vicinity.

ORGANIZATION OF THE REPORT

The rest of the report is comprised of seven chapters. Chapter 2 summarizes literature related to the performance evaluation of large scale transportation projects, including toll roads. Chapter 3 discussed the data collection and data processing methods adopted for this study. Chapter 4 provides a comprehensive framework adopted for developing travel time distributions and reliability measures. Chapter 5 discusses the efficacy of toll roads in reducing travel time and improving travel time reliability on links within its vicinity during different phases of toll road construction and operation. Chapter 6 discusses temporal variations in the effect of toll roads on travel time reliability over time, over different years of toll operation. Lastly, Chapter 7 presents the conclusions from this research.

II. LITERATURE REVIEW

Congestion pricing, also known as variable tolling, is an active policy in the field of traffic congestion management, which focuses on managing transportation demand.[3] Congestion pricing strategy is based in the 'marginal cost pricing' principle of economics.[4] In the context of traffic, this is a pricing strategy aimed at minimizing the total cost of travel over all travelers together, by charging each traveler a fee equal to the dollar-value-equivalent cost of the incremental delay levied by the traveler on other travelers. By keeping a higher traveler fee during the peak period, some travelers could be disincentivized from making less-important trips during peak hours, incentivized to defer them, or incentivized to follow alternate routes.

Many researchers have considered road pricing to be an effective strategy for reducing road traffic congestion.[5] The decisions to implement pricing strategies are usually made using regional travel demand forecasting models and long-term transportation planning process. Anomalies associated with such model outcomes are mainly related to their theoretical and empirical limitations in real-world applications[6] and to the difficulty of predicting travelers' behavioral responses to tolls.[7] In light of these problems, some researchers have studied the possibility of incorporating Macroscopic Fundamental Diagrams (MFDs) to model congestion reduction and the travel time savings as a function of the amount of toll paid. [8]

The results of theoretical modeling and analysis of pricing strategies are not, however, guaranteed to correspond to reality, and indeed sometimes they do not. Some researchers have discussed anomalies associated with the traffic forecast and actual traffic on toll roads.[9] Li and Hensher assessed the error in toll road traffic forecast by considering various toll roads in Australia.[10] Study results indicated an average error of 45% in traffic forecast on the Hills M2 Motorway, the Westlink M7, Cross City Tunnel, and the Eastlink. Welde discussed the risk associated with the inaccurate forecast of traffic based on the Norwegian toll projects evaluation.[11] As the success of a toll road project is highly dependent on actual performance, rather than on merely predicted performance, it is important that the actual performance of toll roads be monitored and evaluated over a range of years of operation.[12] As more of these toll facilities are planned and constructed in the United States, it is essential for agencies to analyze, understand and evaluate how these facilities may operate over time through.

One of the general measures of transportation project performance is cost-benefit analysis.[13] Monetary benefits of the toll road have also been reviewed by Oh et al.[14] They discussed road pricing, revenue generation, and the cost associated with the toll road project. Anas and Lindsey analyzed road pricing theory and available policy options based on policy outcomes from Singapore, London, Stockholm, and Milan.[15] They evaluated the potential benefits of toll projects in light of the benefits and costs, the availability of public transportation, and public acceptance. Chi et al. (2017) studied various methods of toll road evaluation based on the research purpose like revenue risk exposure, benefits and costs, traffic forecasts, public interest on toll roads, road pricing theory, etc.[16] Their study also includes and summarizes a comprehensive list of previous research on assessment of toll road projects.

DeCorla-Souza compared various pricing alternatives, or toll options, with traditional free highway alternatives, using the data from the Capital Beltway project.[17] His research employed the Spreadsheet Model for Induced Travel Estimation (SMITE) from the Federal Highway Administration (FHWA). The benefits associated with the pricing strategies were evaluated based on various indicators, including delay reduction, toll revenue, transit subsidy, and user benefits. The results from his research indicated that pricing alternatives are much efficient and effective than conventional alternatives that do not use tolls.

The National Highway Cooperative Research Program (NCHRP) report entitled "Guidebook for Assessing the Social and Economic Effects of Transportation Projects" illustrates various methods, tools, and techniques for the assessment of transportation projects based on the social and economic implications to the communities.[18] This document has provided the effects of transportation projects for two categories; the transportation system effects and the social and economic effects. Transportation effects include effects on travel time benefits, safety, vehicle operating cost and choice of mode of travel, while economic effects include effects on community cohesion, economic development, traffic noise, and visual quality.

Kalmanje and Kockelman studied the effect of the toll road on socio-economic and traffic characteristics in Texas.[19] 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. The findings from their study indicate that congestion reduction was concentrated within a mile neighborhood of the toll road.

PERFORMANCE EVALUATION: TRAVEL TIME RELIABILITY

Performance evaluation is critical to the success of long-term transportation projects, especially at the beginning of their operation. The majority of transportation projects are mainly aimed at achieving congestion reduction. A comprehensive list of various traffic performance measures is summarized in the NCHRP report on "Evaluation and Performance Measurement of Congestion Pricing Projects."[20] This report lists various measures of traffic performance: speed and travel time; traffic volume; VMT; congestion; mode share; vehicle occupancy; and bike/pedestrian counts.

In recent times, due to the increased availability of traffic data from various sources, researchers have expanded the metrics for highway performance from static measures to include travel time-based measures. In addition, improving travel time or saving travel time can be considered as the first derived benefit of a toll road project. While discussing the improvement in travel time, the reduced variability in travel time must also come into consideration. High variability in travel time equates to a less-reliable transportation system,[21] and demands that travelers include additional time or extra time on their daily trips to ensure on-time arrival.[22]

Researchers have begun to realize the benefits of travel time reliability-based performance evaluation over traditional methods which only evaluate average travel time (ATT). Travel time reliability has been called as "an important measure of service quality for travelers,"[23] and has been used to measure the operational performance of arterial streets.[24] Various types of reliability measures exist: buffer measures; statistical measures; and delayed trip indicators. A report from the FHWA has stated that the most effective measures of travel time reliability are: the Planning Time, defined as the 95th percentile travel time (PT); the Buffer Time (BT), defined as the difference between PT and ATT; and the Buffer Time Index (BTI), defined as the ratio of BT to ATT.[25]

Wakabayashi and Matsumoto performed a comparative assessment of various travel time reliability measures for performance evaluation.[26] According to their findings, the combination of ATT and an appropriate travel time reliability index is important for assessing the travel time reliability of a route from the user and operator perspective. Goodin et al. proposed BTI and another measure, the Planning Time Index (PTI), defined as the ratio of PT to free-flow travel time for the performance evaluation of managed lanes.[27] Likewise, Pulugurtha et al. suggested BTI and PTI for comparing the road links/corridor performance.[28] Reliability measures such as BT and PT can be used to compare the conditions of a road before and after a transportation project.[29] The effect of transportation projects can also be quantified using ATT and BT.[30]

A summary of travel time reliability measures that can be used for the toll road and near vicinity corridor performance evaluation based on past research is presented in Table 1.

Table 1. Travel Time System Performance Measures

Index	Formula
Buffer Time (BT)	$TT_{95} - TT_{Avg}$
Buffer Time Index (BTI)	$\frac{TT_{95} - TT_{Avg}}{TT_{Avg}} \times 100$
Planning Time (PT)	TT_{95}
Planning Time Index(PTI)	$TT_{95}/\textit{Free flow travel time}$

LIMITATIONS OF PREVIOUS RESEARCH

Toll road projects are mainly aimed at reducing the demand for transportation on congested corridors, by segregating travelers based on their valuing of time and their need for travel. The success of toll projects depends on the fact that drivers value both their time and their money that these values are commensurable, and that drivers make their driving decisions by comparing these values. However, this is a challenge for transportation planners, because based on the pricing, travelers are free to decide whether to use the toll road or not.. Decisions whether to implement toll roads and express toll lanes, and on how to price them, are made through the use of regional travel demand forecasting models and long-term transportation planning process. Since there is no guarantee that real-world results will conform to the projections of such studies, the effectiveness of toll roads in mitigating traffic congestion and improving travel time needs to be monitored and evaluated frequently after the implementation. The spatial and temporal variations in travel demand along the region’s traffic network after the deployment of toll roads should also be considered in the performance evaluation process.

Presently, while considering the effectiveness of toll roads, there are many research gaps related to the performance evaluation based on the far fewer research work. To date, there are no effective travel time reliability measures (existing measures) proposed for the assessment of the performance of long-term transportation projects like express lanes and toll lanes. The majority of research has neglected the spatial and temporal dependence of large-scale transportation projects' effects on the region's traffic and system performance. Therefore, the main objective of this research is to develop a systemic analytical framework to evaluate the effect of toll roads on region's traffic using travel time and travel time reliability measures, over space (proximity to the toll road) and time (years of toll road operation).

III. STUDY AREA, DATA COLLECTION, AND DATA PROCESSING

This chapter presents the study area and the data collection and data processing methods for this research.

STUDY AREA

The Triangle Expressway is the first expressway in the state of North Carolina, United States to employ all-electronic tolling technology. The Triangle Expressway was constructed to relieve congestion on NC 55 (a parallel alternate road) while improving access to the Research Triangle Park.[31] It is an 18.8-mile long 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 in three different phases. Phase 1 was a Greenfield project that extended from NC 147 (Durham Freeway) south to meet NC 540, which at the time terminated right at NC 54. The segment constructed during Phase 1, the NC 147 portion, is referred to as the Triangle Parkway. The next two segments, constructed during Phase 2 and Phase 3, cut through all the way down to Holly Springs and are together referred to as the Western Wake Parkway. The construction of all three segments began at the same time, in August of 2009. Details about different phases of construction of the Triangle Expressway are summarized in Table 2.

Table 2. Different Phases of the Triangle Expressway Construction

Phase/details	Phase 1	Phase 2	Phase 3
Construction Began	August 2009	August 2009	August 2009
Road Opened	December 2011	August 2012	December 2012
Toll Began	January 2012	August 2012	January 2013
Connects	Toll NC 540 between NC 55 and NC 54	Toll NC 540 between NC 54 and US 64 in Apex	Toll NC 540 between US 64 in Apex to NC 55 Bypass in Holly Springs

It is assumed that the spatial and temporal effects of toll roads can be effectively captured by analyzing travel time variations on the toll road and in other nearby corridors. To avoid the toll expense, people may choose to travel on alternative routes too. Thus, the parallel alternate road NC 55 is also included in the travel time reliability assessment. It is assumed that the effect of toll roads would be mainly concentrated within 2-mile vicinity of the toll road. The major cross-streets, US-1 and US-64, are connecting toll road and the parallel alternate route (Figure 1). Hence, there would be a change in travel time reliability in these connecting segments. Also, the effect of the toll road on near vicinity traffic will be different in links which are near to the toll road.

DATA COLLECTION

Raw data pertaining to travel time was collected from the Regional Integrated Transportation Information System (RITIS), with support from NCDOT, at one-minute intervals. The raw database contains data labeled by time-of-the-day, day-of-the-week, average speed, travel time, and reference speed. The reference speed is considered as an uncongested "free flow" speed determined for each TMC or road link. This data is acquired from various sources, including traffic sensors (induction loop radar sensor, toll tag reader, etc.), probe vehicles, and the smart dust network. The probe network contains hundreds of thousands of vehicles enabled with Global Positioning System technology (GPS) and advanced transmitting capabilities.[32]

The data corresponding to each link is coded with a 9-digit identification code, referred to as the TMC code. In this report, a 3-digit ID was generated for each individual TMC or link for easy understanding. The first character stands for the type of road: T is toll road; P is a parallel alternate road; and C is cross-street. The second character is a numeric starting from 1. The third character denotes the direction of traffic movement: N is northbound; S is southbound; E is eastbound; and W is westbound. For instance, 'P1N' indicates the first link on the parallel alternate road in the northbound direction.

The travel time data was collected for four different time periods: before construction; during Phase 1 operation; during Phase 2 operation; and after opening the toll road for complete service (Phase 3).

Some links in the area are less than 0.05 miles in length (264 ft.); these were excluded from the present research and analysis. The travel time for these links will be of small range, typically less than ten seconds, and the variability of travel time cannot therefore be reliably captured from such a small segment. In addition, the travel time data corresponding to some of the links are not available in the database; those links were also excluded from the analysis.

SELECTION OF PERFORMANCE MEASURES

Based on past research, four measures were considered in this study. They are briefly described as follows.

1. Average Travel Time (ATT)

2. Planning Time (PT): Planning time is the 95th percentile travel time. It gives a clear indication of how bad delay might be, on specific routes during the heaviest traffic days.

3. Buffer Time (BT): Buffer time is the difference between the 95th percentile travel time and the ATT. It represents the extra time that most travelers add to their ATT for the on-time completion of their trip. BT is computed using equation 1:

$$BT = PT - ATT \tag{1}$$

4. Buffer Time Index (BTI): This is the ratio of Buffer Time to the Average Travel Time. BTI is computed using equation 2:[33]

$$BTI = BT / ATT \tag{2}$$

DATA PROCESSING

The segregation of data was carried out in two levels: Geographic Information Systems (GIS) based link identification and travel time data processing using Microsoft SQL.

GIS-Based Link Identification

ArcGIS software was used to identify links within the toll road vicinity. Geo-referencing of the links was done using four well-defined points collected from the RITIS: start latitude; start longitude; end latitude; and end longitude. The road network data was obtained in a geospatial format (shapefile) from NCDOT. A buffer zone of 2-miles was generated along the Triangle Expressway. The links within the 2-mile buffer zone were then identified on the cross-streets. A processed ArcGIS snapshot is shown in Figure 2.

Four near vicinity corridors were considered in this research. In Figure 2, the black dotted line indicates the parallel alternate road (NC 55), while the black solid lines represent the major cross-streets (US 64, NC 54, and US 1).

Travel Time Data Processing

Data corresponding to weekday and weekend traffic (7:00 a.m. to 8:00 a.m., 12:00 p.m. to 1:00 p.m., 5:00 p.m. to 6:00 p.m., and 8:00 p.m. to 9:00 p.m.) were separated using Microsoft SQL and RStudio package. The effect of recurrent congestion can be effectively quantified from the travel time reliability assessment of the aforementioned peak-hours. The peak-hour delay associated with the travel corridor can creates uncertainty among the drivers, since they may not have a clear idea about the required time to reach the destination. It is therefore very important to capture the variability in travel times using travel time reliability measures; in this case, ATT, PT, BT, and BTI were used for the assessment process.

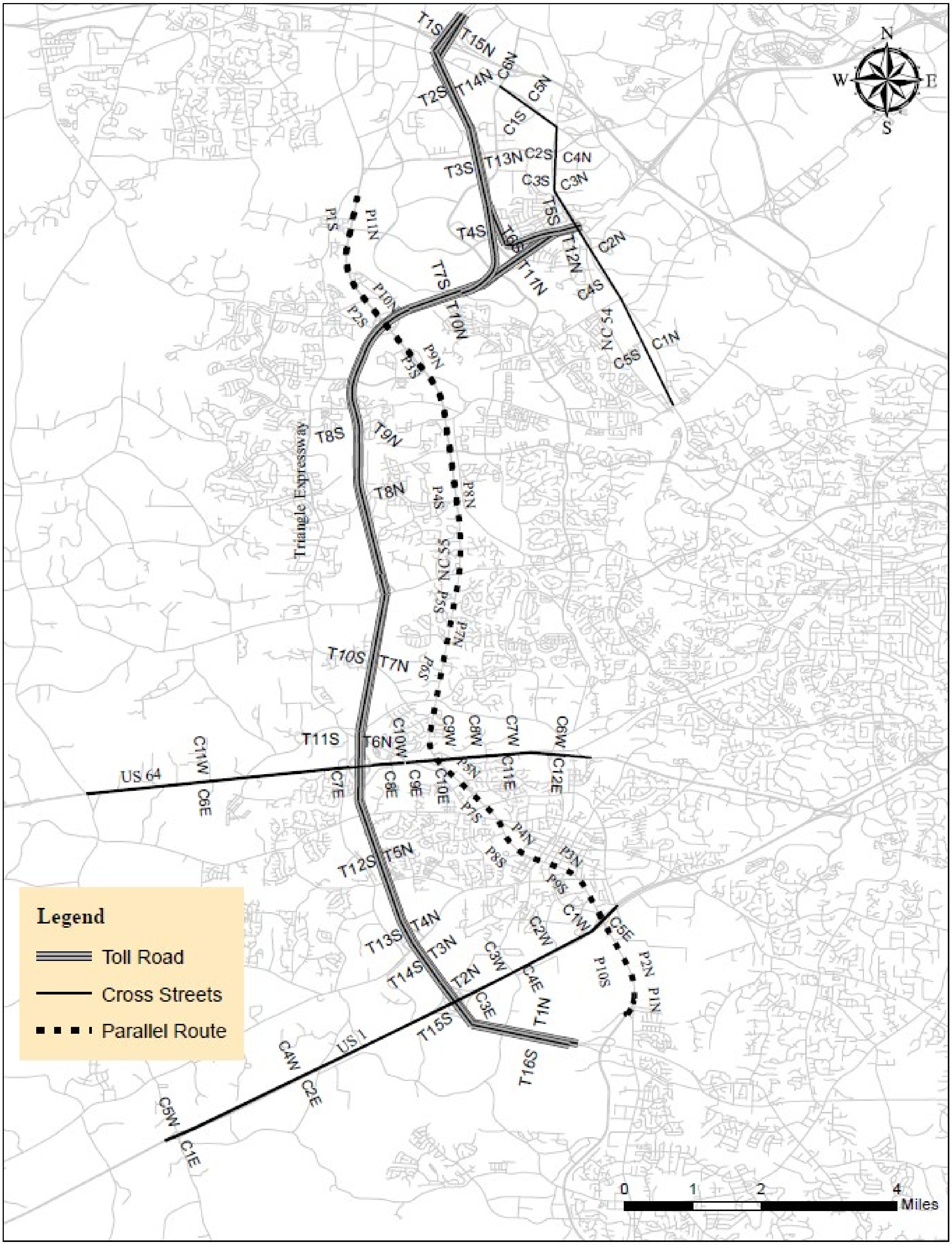

Figure 2. Links Selected for the Present Research

IV. METHODOLOGY

This chapter presents the methodological framework adopted in this research. Figure 3 represents the systematic procedure followed in this research.

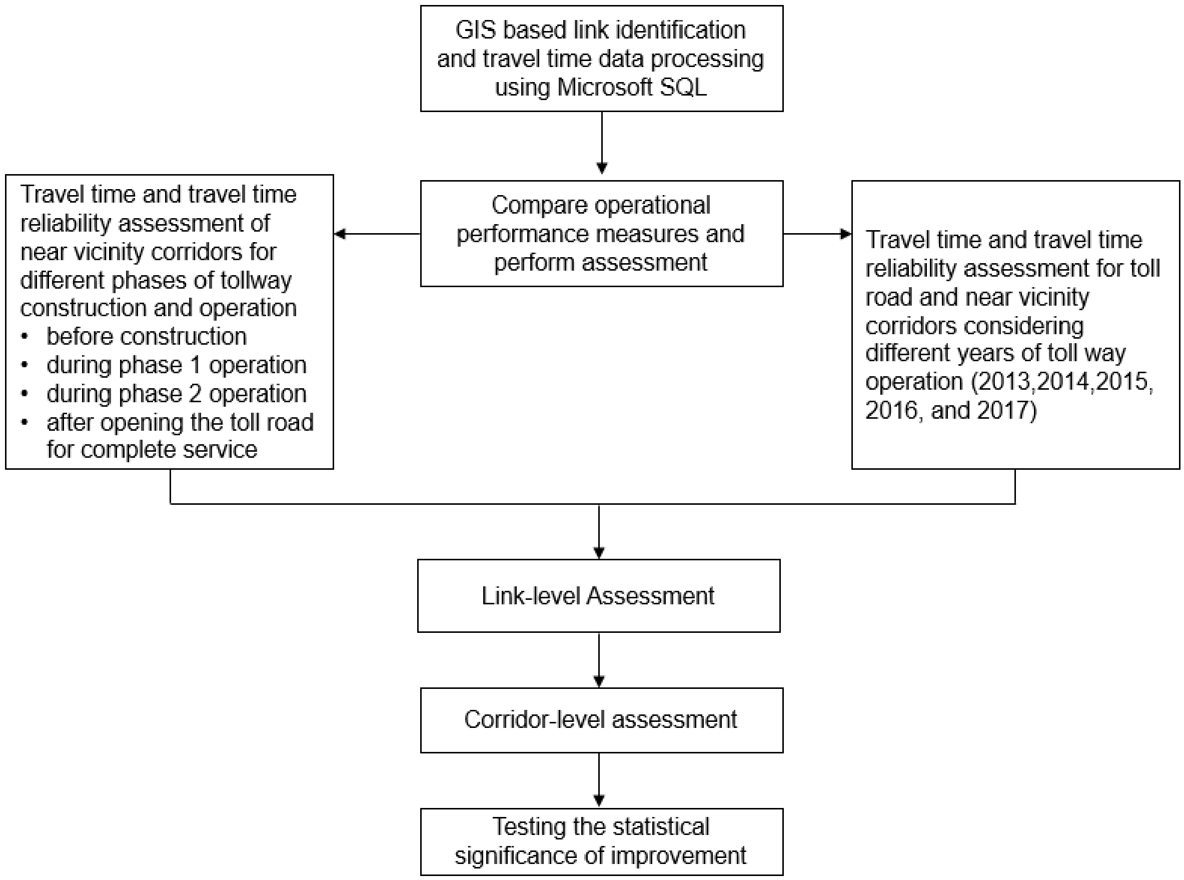

Figure 3. Methodology

TRAVEL TIME AND TRAVEL TIME RELIABILITY MEASURES

The analysis of the data was carried out separately for the toll road, parallel alternate road, and near-vicinity corridors. In the first part, initial analysis was carried out for different phases of construction and after opening the toll road for providing service. In the second part, travel time and travel time reliability measures were computed for 2013, 2014, 2015, 2016, and 2017 for links along the toll road, parallel alternate route, and the near vicinity cross-streets.

Part 1: Travel time-based performance evaluation for different phases of toll road construction and operation

Travel time and travel time reliability measures for the parallel alternate road and for the cross-streets were computed for different scenarios: before construction; during Phase 1 operation; during Phase 2 operation; and after opening the toll road for complete service

(Phase 3). This part of the analysis was helpful in assessing the effectiveness of the toll road in improving operational performance within its vicinity, over time through the three construction phases and after the completion of the whole project. In the initial stage, computation of the travel time reliability was planned for the years 2010, 2011, 2012, and 2013 for links within the vicinity of the toll road (prior to construction and after opening the toll road for providing service); however, unavailability of travel time data for the year 2010 was one difficulty that has arisen in the travel time reliability assessment. It is for this reason that the construction period was divided into longer for the purposes of analysis. Based on the available travel time data, analysis periods are finalized as follows:

- Before construction: September 2011 – December 2011
- Phase 1 operation: February 2012 – May 2012
- Phase 2 operation: September 2012 – May 2012
- After opening the toll road for complete service (Phase 3): February 2013 – May 2013

The travel time and travel time reliability measures for different operational phases of the Triangle Expressway were compared to the same measures for the before-construction phase. Finally, a comparison of the annual average daily traffic (AADT) along the parallel alternate road and cross-streets before the construction of the toll road and after opening the toll road for the complete service was also performed.

Part 2: Travel time-based performance evaluation for different years of toll road operation

The travel times and travel time reliabilities of the toll road, parallel road, and cross-streets were studied over different years of toll road operation. This part of the study was mainly aimed at quantifying the change in the effectiveness of the toll road over time. It was expected to be highly likely that traffic conditions within the vicinity of the toll road would have changed over the years, firstly due to the general growth in traffic conditions over time, and secondly due to the toll road, which could both negatively influence traffic volume on nearby links due to assimilation of drivers, and positively influence traffic volume on nearby links due to induced demand.

LINK-LEVEL ASSESSMENT

The link-level analysis gives a clear picture of the travel time variations on a road. The variation in travel times for each link under varying road characteristics and traffic conditions during different periods of the day can capture the travel time variability more efficiently than could be achieved by only looking at the aggregate-level.

CORRIDOR-LEVEL ASSESSMENT

To quantify overall improvement in travel time reliability measures, a corridor-level assessment, conducted separately for the parallel alternate road and for the cross-streets, was performed. In the corridor-level assessment, cumulative distribution functions for travel times were generated at an aggregate level. Data normalization was carried out by dividing the travel times with the length of each link. This was done primarily because travel times depend on link length and posted speed limit in addition to traffic, control, and environmental conditions.

TESTING THE STATISTICAL SIGNIFICANCE OF IMPROVEMENT

The statistical significance of the change in travel time performance measures was evaluated using the one-tailed paired t-test. The analysis was performed at a 95% confidence level. For Part 1 (the construction period), the null hypothesis was that the difference between the actual means of the travel time performance measures before construction, and each phase of toll road operation, is zero; since the t-test is one-tailed, the alternative hypothesis assumes that the difference between these actual mean performance measures is negative. For Part 2 (the fully operational period), the null hypothesis assumes that the difference between the actual means of the travel time performance measures between a pair of consecutive years is zero. The alternative hypothesis assumes that the difference between the actual means of the selected performance measures is negative.

V. TRAVEL TIME-BASED PERFORMANCE EVALUATION FOR DIFFERENT PHASES OF TOLL ROAD CONSTRUCTION AND OPERATION

This chapter presents the results obtained from the travel time and travel time reliability assessment of the links adjacent to the toll roads (both the parallel alternate road and the cross-streets) for different phases of toll road construction and operation: before construction; during Phase 1 operation, during Phase 2 operation, and after opening the toll road for complete service (Phase 3). A comparison of the annual average daily traffic (AADT) along the parallel alternate road and cross-streets before the construction of toll road and after opening the toll road for the complete service was also performed.

LINK-LEVEL ANALYSIS

Travel time reliability measures for the parallel alternate road and cross-streets were computed for different scenarios before construction: during Phase 1 operation; during Phase 2 operation; and after opening the toll road for complete service (Phase 3). As a preliminary approach, the analysis was performed at the link level, with links varying in length, but all greater than 0.05 miles long. For each selected link with available travel time data, the ratio was computed between the travel time reliability measures for the chosen phase to the same measure for the before-construction phase. A ratio greater than one indicates a worsening of the travel time reliability measure over the period, while a ratio less than one indicates an improvement in the travel time reliability measure during the same period.

Table 3 summarizes the results from the analysis performed for the parallel alternate road, for morning peak hour on a typical weekday. The highlighted grey-shaded cells indicate worsening of the travel time reliability measure compared to the before construction. For example, while considering link ‘P3S’, the value corresponding to the percentage change in Phase 1 is reported as 1.01, which implies there is a 1% increase in ATT during Phase 1 compared to the before construction phase. The extent of change in travel time reliability measure is represented by the length of the red colored data bar shown in each cell. Overall, it can be seen that the majority of the links showed a trend of improvement in travel time reliability after each phase of toll road operation; this trend is more consistent for Phase 2 and Phase 3 operation of the Triangle Expressway compared to the before construction phase.

Table 4 summarizes the results for the same kind of analysis, carried out for the evening peak hour on a typical weekday.

Table 3. Travel Time Reliability Measures for the Parallel Alternate Road in the Morning Peak Hour

Link	Length	Percentile Change (ATT)			Percentile Change (PT)			Percentile Change(BT)			Percentile Change(BTI)		
		Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
P3S	1.45	1.01	0.99	0.98	1.03	0.98	0.95	1.18	0.86	0.73	1.15	0.86	0.73
P4S	2.26	1.01	0.99	0.96	0.95	0.98	0.89	0.57	0.89	0.38	0.56	0.89	0.39
P5S	1.86	1.02	1.00	0.96	1.00	0.93	0.87	0.88	0.53	0.35	0.86	0.53	0.36
P6S	0.82	1.03	1.01	0.99	1.11	1.11	0.97	2.38	2.63	0.75	2.27	2.56	0.74
P7S	1.02	0.97	1.00	0.97	0.97	1.11	1.03	0.96	1.96	1.57	0.97	1.93	1.59
P8S	0.78	0.96	0.94	0.94	0.84	0.84	0.90	0.44	0.50	0.78	0.47	0.53	0.83
P9S	1.18	0.94	0.95	0.95	0.96	1.00	0.96	1.11	1.48	1.04	1.15	1.53	1.07
P10S	1.40	1.02	1.01	1.01	1.05	1.00	1.02	1.32	1.00	1.14	1.29	0.99	1.12
P1N	0.76	1.19	0.91	0.83	1.25	0.68	0.45	1.30	0.47	0.11	1.09	0.52	0.13
P2N	1.37	1.05	0.95	0.68	1.00	0.85	0.78	0.90	0.63	1.02	0.86	0.67	1.51
P3N	1.18	0.97	0.95	0.87	0.84	0.84	0.64	0.63	0.67	0.23	0.65	0.70	0.27
P4N	0.78	0.96	0.98	0.94	0.93	0.97	0.88	0.79	0.95	0.53	0.82	0.97	0.56
P5N	1.02	0.96	0.93	0.95	0.96	0.81	0.81	0.98	0.40	0.34	1.01	0.42	0.35
P6N	0.80	0.98	0.94	0.96	0.95	0.84	0.92	0.82	0.47	0.76	0.82	0.49	0.78
P7N	1.86	1.05	0.99	0.96	1.26	1.05	1.00	2.94	1.53	1.34	2.81	1.55	1.41
P8N	2.26	1.03	0.98	0.94	1.09	0.93	0.91	1.45	0.62	0.74	1.40	0.63	0.78

Note: Grey highlighted cells indicate worsening of the travel time reliability measure; red bars indicate the degree of change in travel time reliability over different phases of toll road operation.

Table 4. Travel Time Reliability Measures for the Parallel Alternate Road in the Evening Peak Hour

Link	Length	Percentile Change (ATT)			Percentile Change (PT)			Percentile Change(BT)			Percentile Change(BTI)		
		Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
P3S	1.45	0.93	0.87	0.91	1.00	0.76	0.73	1.23	0.41	0.16	1.31	0.46	0.17
P4S	2.26	1.10	1.00	0.97	1.17	0.92	0.90	1.46	0.59	0.63	1.31	0.59	0.65
P5S	1.86	1.00	0.98	0.95	0.95	0.88	0.86	0.70	0.40	0.43	0.69	0.41	0.44
P6S	0.82	1.01	0.98	0.97	1.22	0.98	0.90	3.25	1.00	0.33	2.98	0.94	0.32
P7S	1.02	1.06	1.04	0.98	1.37	1.14	0.90	2.57	1.49	0.59	2.43	1.43	0.61
P8S	0.78	1.04	0.99	0.82	2.00	1.76	0.54	3.44	2.90	0.12	3.31	2.93	0.14
P9S	1.18	1.00	0.96	0.84	1.11	0.91	0.56	1.23	0.86	0.25	1.23	0.89	0.30
P10S	1.40	0.96	1.24	1.15	0.86	1.33	1.85	0.65	1.53	3.27	0.67	1.25	2.85
P1N	0.76	0.95	1.00	0.97	0.93	1.03	0.96	0.63	1.50	0.75	0.63	1.45	0.74
P2N	1.37	1.05	1.01	0.95	1.12	1.12	0.91	1.38	1.53	0.77	1.30	1.50	0.80
P3N	1.18	0.93	0.98	0.95	1.00	1.00	0.82	1.19	1.06	0.47	1.29	1.09	0.50
P4N	0.78	0.93	0.95	0.94	0.88	0.88	0.85	0.66	0.59	0.47	0.70	0.62	0.49
P5N	1.02	0.93	0.95	0.94	1.00	0.96	0.83	1.21	0.99	0.53	1.29	1.03	0.56
P6N	0.80	1.03	0.97	0.97	1.05	0.84	0.90	1.11	0.39	0.67	1.06	0.39	0.68
P7N	1.86	1.01	1.04	1.02	1.02	1.12	1.02	1.12	1.61	1.10	1.10	1.54	1.07
P8N	2.26	1.01	1.01	1.00	1.07	1.02	1.02	1.74	1.15	1.30	1.68	1.11	1.27

Note: Grey highlighted cells indicate worsening of the travel time reliability measure; red bars indicate the degree of change in travel time reliability over different phases of toll road operation.

From Table 4, it can be seen that the travel time reliability measures for Phase 1 and Phase 2 showed a trend of worsening for the selected links in the parallel alternate road. For Phase 3 (after opening the toll road for complete service), in contrast, the travel time reliability measures improved. The performance in terms of BT and BTI worsened during Phase 1 for the majority of the links. The highways with higher BT and BTI depict the lack of reliability from the operator perspective.[34] In Phase 3, improvements in BT and BTI measures were observed for the majority of the selected links. As BT and BTI indicate the extra time for a trip required to account for unexpected delays, the trend in their reduction can be considered as a positive effect of the Triangle Expressway on the region's traffic.

Table 5 shows the travel time reliability measures for cross-streets (US 64, NC 54, and US 1) during the morning peak hour on a typical weekday. ATT and PT improved during all phases; however, BT and BTI showed a mixed results.

Table 6 shows the travel time reliability measures for cross-streets during the evening peak period on a typical weekday. Similarly, to the weekday morning peak period, ATT and PT showed a clear improvement in all the operational phases. BT and BTI worsened for many links for Phase 1 and Phase 2. For Phase 3, after opening the toll road for complete operation, in terms of the percentage of miles along the cross-streets with an improvement in travel time reliability, 80–85% of the total cross-street miles showed improvements in BT and BTI.

Table 5. Travel Time Reliability Measures for the Cross-Streets in the Morning Peak Hour

Link	Length	Percentile Change (ATT)			Percentile Change (PT)			Percentile Change (BT)			Percentile Change (BTI)		
		Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
C1S	0.90	0.97	0.96	0.99	1.03	0.97	1.03	2.33	1.33	2.00	2.14	1.26	1.94
C2S	0.92	0.94	0.95	0.93	0.87	0.93	0.87	0.62	0.86	0.67	0.64	0.88	0.70
C4S	1.72	0.94	0.96	0.99	0.89	0.97	1.00	0.59	1.02	1.06	0.64	1.06	1.07
C5S	1.69	0.95	0.99	0.98	0.91	1.03	0.89	0.63	1.33	0.25	0.66	1.35	0.27
C1N	1.69	0.94	0.96	0.98	0.94	0.97	0.97	0.89	1.03	0.86	0.95	1.09	0.87
C2N	1.73	1.01	0.98	0.97	1.10	0.94	0.91	1.79	0.68	0.53	1.79	0.72	0.55
C4N	0.92	0.96	0.95	0.96	0.97	0.87	0.81	0.98	0.55	0.23	1.00	0.58	0.25
C5N	0.90	0.95	1.01	0.94	1.03	1.39	1.03	2.10	7.00	2.20	2.10	6.45	2.24
C3E	1.62	1.00	1.07	1.00	0.97	1.06	0.97	0.50	0.90	0.50	0.58	0.86	0.57
C5E	0.45	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.15	1.00	1.02
C1W	0.50	1.00	1.00	0.98	1.04	1.02	1.00	3.00	2.00	2.00	2.64	1.99	1.82
C3W	2.93	1.00	1.05	1.00	1.00	1.07	1.00	1.00	1.31	1.00	1.00	1.21	1.01
C7E	0.38	1.00	0.98	0.93	0.98	0.94	0.90	0.80	0.60	0.60	0.95	0.74	0.69
C9E	0.13	0.93	0.93	0.87	0.89	1.00	0.83	0.50	1.50	0.50	0.63	1.30	0.60
C10E	0.50	0.98	0.98	0.98	0.96	0.96	0.93	0.75	0.75	0.25	0.74	0.66	0.39
C11E	0.85	0.99	0.99	0.97	0.97	0.98	0.97	0.67	0.83	1.00	0.77	0.96	1.15
C7W	0.83	0.99	0.98	0.98	1.00	0.99	0.99	1.33	1.33	1.33	1.20	1.22	1.20
C8W	0.33	0.97	0.97	0.97	0.89	0.89	0.89	0.40	0.40	0.40	0.47	0.44	0.51
C9W	0.34	0.98	0.93	0.88	1.00	0.88	0.75	1.10	0.70	0.20	1.12	0.74	0.31
C11W	3.15	1.00	1.00	0.97	1.06	1.04	1.00	2.25	1.88	1.63	2.28	1.94	1.72

Note: Grey highlighted cells indicate worsening of the travel time reliability measure; red bars indicate the degree of change in travel time reliability over different phases of toll road operation.

Table 6. Travel Time Reliability Measures for the Cross-Streets in the Evening Peak Hour

Link	Length	Percentile Change (ATT)			Percentile Change (PT)			Percentile Change (BT)			Percentile Change (BTI)		
		Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
C1S	0.90	1.03	1.01	0.99	1.25	1.09	1.06	4.40	2.20	2.21	3.91	2.06	2.07
C2S	0.92	0.96	0.96	0.97	0.81	0.83	0.73	0.41	0.51	0.13	0.43	0.54	0.14
C4S	1.72	0.87	0.98	1.00	0.74	1.28	0.77	0.37	2.15	0.10	0.44	2.19	0.10
C5S	1.69	0.93	1.02	1.04	0.89	1.06	0.94	0.85	1.12	0.83	0.91	1.09	0.80
C1N	1.69	0.96	1.00	1.00	1.00	1.20	0.97	1.29	2.49	0.79	1.36	2.46	0.79
C2N	1.73	0.98	0.98	0.98	1.00	1.00	0.91	1.14	1.14	0.44	1.16	1.16	0.45
C4N	0.92	0.95	0.97	1.00	1.04	1.04	0.83	1.38	1.32	0.24	1.48	1.39	0.24
C5N	0.90	0.94	0.89	0.89	0.81	0.72	0.72	0.43	0.23	0.23	0.47	0.27	0.26
C3E	1.62	0.99	0.99	0.98	1.00	1.00	1.00	1.29	1.29	1.60	1.29	1.36	1.61
C5E	0.45	0.98	1.00	1.00	0.95	0.98	0.98	0.67	0.67	1.06	0.68	0.95	1.05
C1W	0.50	1.06	0.96	0.90	1.35	0.89	0.74	2.46	0.62	0.21	2.20	0.64	0.22
C3W	2.93	1.00	1.01	0.99	0.99	0.99	0.99	0.78	0.67	1.00	0.77	0.68	0.96
C7E	0.38	1.00	1.05	0.96	1.00	1.04	0.93	1.00	1.00	0.82	1.13	1.07	0.76
C9E	0.13	1.07	1.07	0.94	1.13	1.44	0.88	2.00	7.00	0.88	2.16	5.93	0.82
C10E	0.50	0.98	0.98	0.95	1.00	1.00	0.95	1.50	1.50	1.32	1.19	1.40	0.99
C11E	0.85	1.00	0.98	0.95	1.02	0.97	0.95	1.33	0.83	1.01	1.24	0.79	0.96
C7W	0.83	1.00	1.01	0.99	1.00	1.02	1.00	1.00	1.25	1.44	1.07	1.38	1.42
C8W	0.33	1.00	1.00	0.99	1.00	1.00	0.97	1.00	1.00	1.11	1.21	1.09	1.07
C9W	0.34	1.00	1.00	0.92	1.04	1.04	0.76	1.18	1.18	0.29	1.15	1.13	0.30
C11W	3.15	1.01	0.99	0.98	1.04	1.00	0.98	1.48	1.09	1.06	1.48	1.09	1.08

Note: Grey highlighted cells indicate worsening of the travel time reliability measure; red bars indicate the degree of change in travel time reliability over different phases of toll road operation.

CORRIDOR-LEVEL ANALYSIS

The outcomes from the link-level analysis indicate a clear trend of improvement in travel time reliability on the majority of the selected links, which are all within a 2-mile distance from the toll road. Furthermore, to quantify the variability in travel time, a corridor-level assessment, conducted separately for the parallel alternate route and for cross-streets, was performed. As it is a corridor-level assessment, to quantify the overall benefit of the toll in decreasing the travel time, all the operation phases are considered in the analysis process. A cumulative distribution function for travel times was generated for each operating phase of toll road construction and operation. Cumulative distribution of travel times in a corridor is useful for analyzing the variations in travel times. It helps visualize the travel time trends for multiple time periods in a single graph. Most importantly, it provides the magnitude of travel times along with the distribution of travel times in a specific time period. It is a good method for comparing before and after median travel times, and changes in interquartile range, in order to assess the travel time reliability. The variability in travel times can be clearly visualized and interpreted from the travel time cumulative distribution function. Data normalization was carried out by dividing the travel time with the length of each link. Figure 4 summarizes the cumulative distribution of per-mile travel times for the parallel alternate route during different phases of toll road operation.

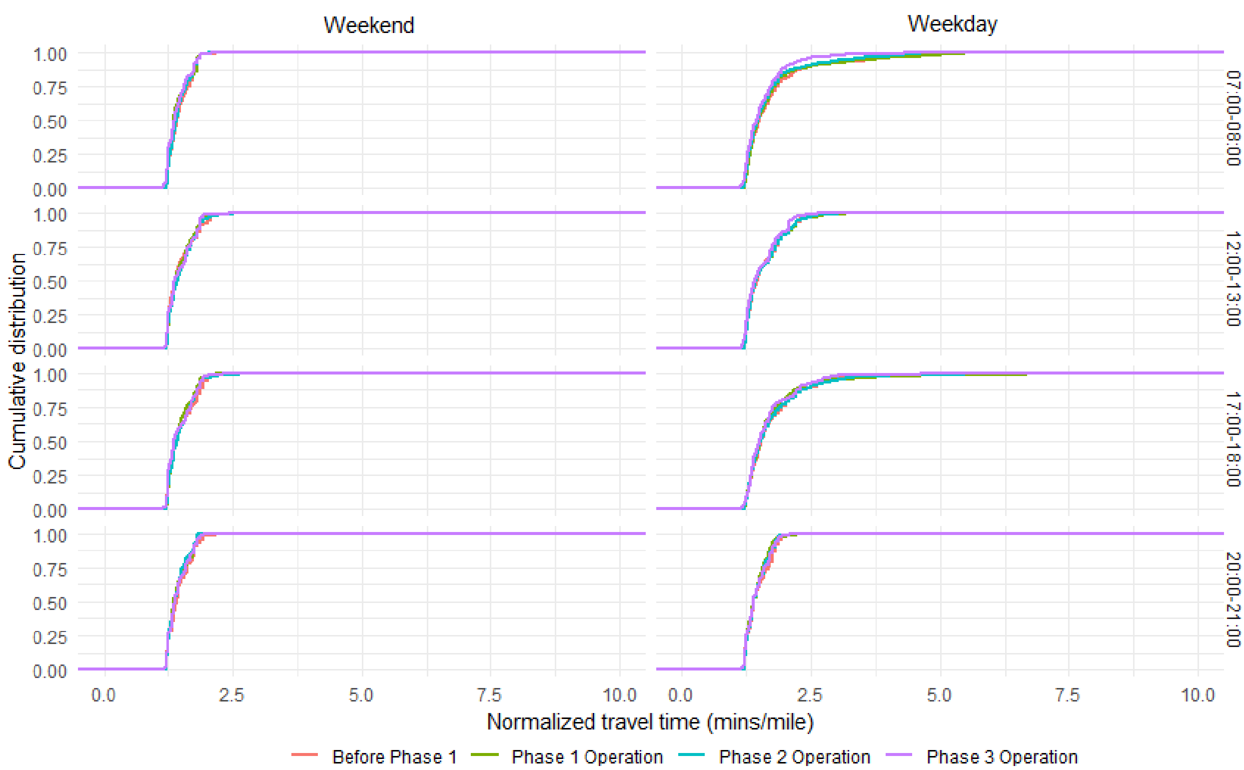

Figure 4. Cumulative Distribution of Travel Times on the Parallel Route

From Figure 4, it can be seen that there exists a similar pattern of cumulative travel time distribution for parallel alternate route during different phases of toll road operation for different peak hours in weekend. In the case of weekdays, a shift in the cumulative travel time distribution (beyond 75th percentile) can be seen in the morning peak hour, specifically, while considering the before construction phase and the Phase 3 operation. In general, the mean travel times is ranged from 1.5–2.5 minutes/mile for all the selected scenarios for all the peak periods in a typical weekday and weekend. It can also be seen that the variations in travel times is found to be low in different operating scenarios.

Figure 5 shows the results of a similar analysis, performed for the near-vicinity cross-streets.

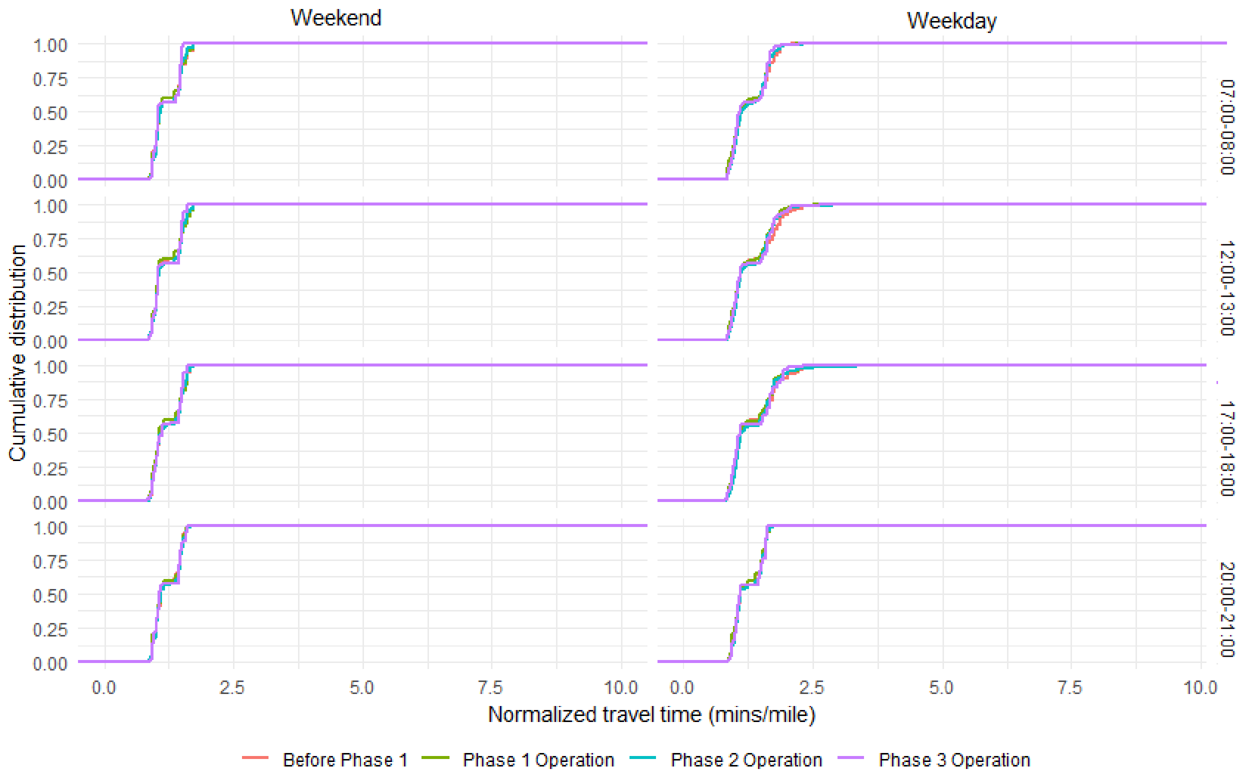

Figure 5. Cumulative Distribution of Travel Times on the Cross-Streets

The cumulative distribution of travel times on the cross-streets show a similar distribution of travel time for all the operating scenarios. There are two modes in the cumulative distribution of travel times for selected hours of the analysis for all the phases of toll road construction. This can be attributed to the differences in travel time samples in the dataset. The inflection points for each case is almost the same in the x-axis, indicating a similar pattern throughout the analysis period. The locations where the modes appear is related to the y-axis, showing the difference in travel time samples in the dataset. The travel times ranged from 1–1.5 minutes/mile for the first mode and 1.5–2.25 minutes/mile for the second mode for all the operating scenarios and selected periods. To test for statistical significance of the observed improvements in travel time reliability measures, one-tailed paired t-test was performed, at a 95% confidence level. The null hypothesis is 'H0: The travel time reliability measure did not differ significantly after the implementation of the Triangle Expressway toll'. The alternative hypothesis is 'H1: The travel time reliability measure reduced (improved) after the implementation of the Triangle Expressway toll'. The test results for the parallel route and cross-streets are summarized in Table 7.

Table 7. Paired T-Test Results for Different Phases of Toll Road Operation

Time period	ATT			PT			BT			BTI		
	1–2	1–3	1–4	1–2	1–3	1–4	1–2	1–3	1–4	1–2	1–3	1–4
Parallel Street- p value												
7:00 a.m. – 8.00 a.m. WEEKDAY	0.19	<0.01	0.03	0.34	0.02	<0.01	0.40	0.03	0.03	0.49	0.05	0.07
12:00 p.m. – 1.00 p.m. WEEKDAY	0.19	0.28	<0.01	0.03	0.08	0.08	0.02	0.05	0.37	0.03	0.06	0.39
5:00 p.m. – 6.00 p.m. WEEKDAY	0.46	0.48	0.03	0.06	0.25	0.14	0.05	0.22	0.18	0.06	0.22	0.13
8:00 p.m. – 9.00 p.m. WEEKDAY	0.06	0.34	0.05	0.37	0.30	0.30	0.21	0.17	0.47	0.26	0.26	0.49
7:00 a.m. – 8.00 a.m. WEEKEND	0.45	0.45	<0.01	0.48	0.47	0.03	0.44	0.39	0.13	0.50	0.45	0.08
12:00 p.m. – 1.00 p.m. WEEKEND	0.26	0.41	0.08	0.25	0.36	0.11	0.15	0.27	0.15	0.13	0.20	0.18
5:00 p.m. – 6.00 p.m. WEEKEND	0.10	<0.01	0.02	0.08	<0.01	<0.01	0.12	<0.01	<0.01	0.17	<0.01	<0.01
8:00 p.m. – 9.00 p.m. WEEKEND	0.06	0.06	<0.01	0.03	0.10	0.02	0.03	0.09	0.02	0.03	0.06	0.03
Cross-Street- p value												
7:00 a.m. – 8.00 a.m. WEEKDAY	<0.01	0.07	<0.01	0.16	0.45	<0.01	0.47	0.23	0.06	0.42	0.32	0.02
12:00 p.m. – 1.00 p.m. WEEKDAY	<0.01	<0.01	<0.01	<0.01	0.21	0.02	0.06	0.06	0.01	0.06	0.21	0.04
5:00 p.m. – 6.00 p.m. WEEKDAY	0.03	0.07	0.02	0.12	0.18	<0.01	0.24	0.12	0.01	0.30	0.12	<0.01
8:00 p.m. – 9.00 p.m. WEEKDAY	<0.01	0.16	<0.01	0.08	0.33	<0.01	0.16	0.40	0.03	0.23	0.20	<0.01
7:00 a.m. – 8.00 a.m. WEEKEND	<0.01	0.11	0.39	0.03	0.30	0.40	0.18	0.13	0.33	0.34	0.11	0.38
12:00 p.m. – 1.00 p.m. WEEKEND	0.03	<0.01	0.07	0.09	0.30	0.12	0.17	0.5	0.21	0.11	0.23	0.36
5:00 p.m. – 6.00 p.m. WEEKEND	0.32	0.19	0.06	0.27	0.10	0.09	0.15	0.03	0.14	0.04	0.03	0.19
8:00 p.m. – 9.00 p.m. WEEKEND	0.35	0.23	0.18	0.02	0.34	0.32	0.02	0.02	<0.01	<0.01	<0.01	<0.01

Note 1: Highlighted: Worsening at the 95% confidence level

Note 2: 1–2: Before construction-Phase 1 operation; 1–3: Before construction-Phase 2 operation; 1–3: Before construction-Phase 3 operation

On a typical weekday morning peak hour, there exists a statistically significant improvement in travel time reliability measures at the 95% confidence level in the parallel route for many of the selected time periods and operating phases. While looking into the afternoon peak, there is a statistically significant worsening of travel time reliability at the 95% confidence level for some of the operating scenarios. Similarly, a statistically significant worsening in travel time reliability at the 95% confidence level was found during the weekend evening peak period during the second phase of the Triangle Expressway operation. It was found that there is a statistically significant improvement in BT and BTI at the 95% confidence level for the weekend nighttime traffic. Many operating scenarios did not show any statistically significant increase or deterioration in travel time reliability, at the 95% confidence level.

In the case of cross-streets, travel time reliability measures were significantly improved after opening the toll road for complete service (Phase 3 operation). ATT and PT improved significantly at the 95% confidence level, and the improvement in BT and BTI for Phase 3 is significant at the 95% confidence level for many operating scenarios. Overall, there is a clear indication of improvement in travel time reliability for cross-streets on typical weekdays.

As mentioned previously, the geospatial and temporal variations in the effects of large-scale transportation projects like toll roads can be quantified using travel time reliability measures. The present study considered a 2-mile buffer zone in order to identify potential links that may get influenced by the toll operation. The results from the one-tail t-test indicate that, on a typical weekday, during all the selected time periods, there exist a positive effect of the toll road in improving travel time reliability on near vicinity corridors.

To substantiate the trend of improvement in reliability measures, a before-after (before construction of the toll road-after opening the toll road for complete service) comparison of AADT along the study corridor was performed. The AADT data was obtained from the NCDOT traffic volume maps. The NCDOT interactive mapping tool gives the AADT for a specific year at a specific point. Figure 6 shows the AADT at the selected counting stations within the vicinity of toll road.

For the parallel route, there is a clear trend of reduction in traffic volume at all the nine AADT counting stations after opening the Triangle Expressway for complete service. For the cross-streets, there is no such consistent trend.

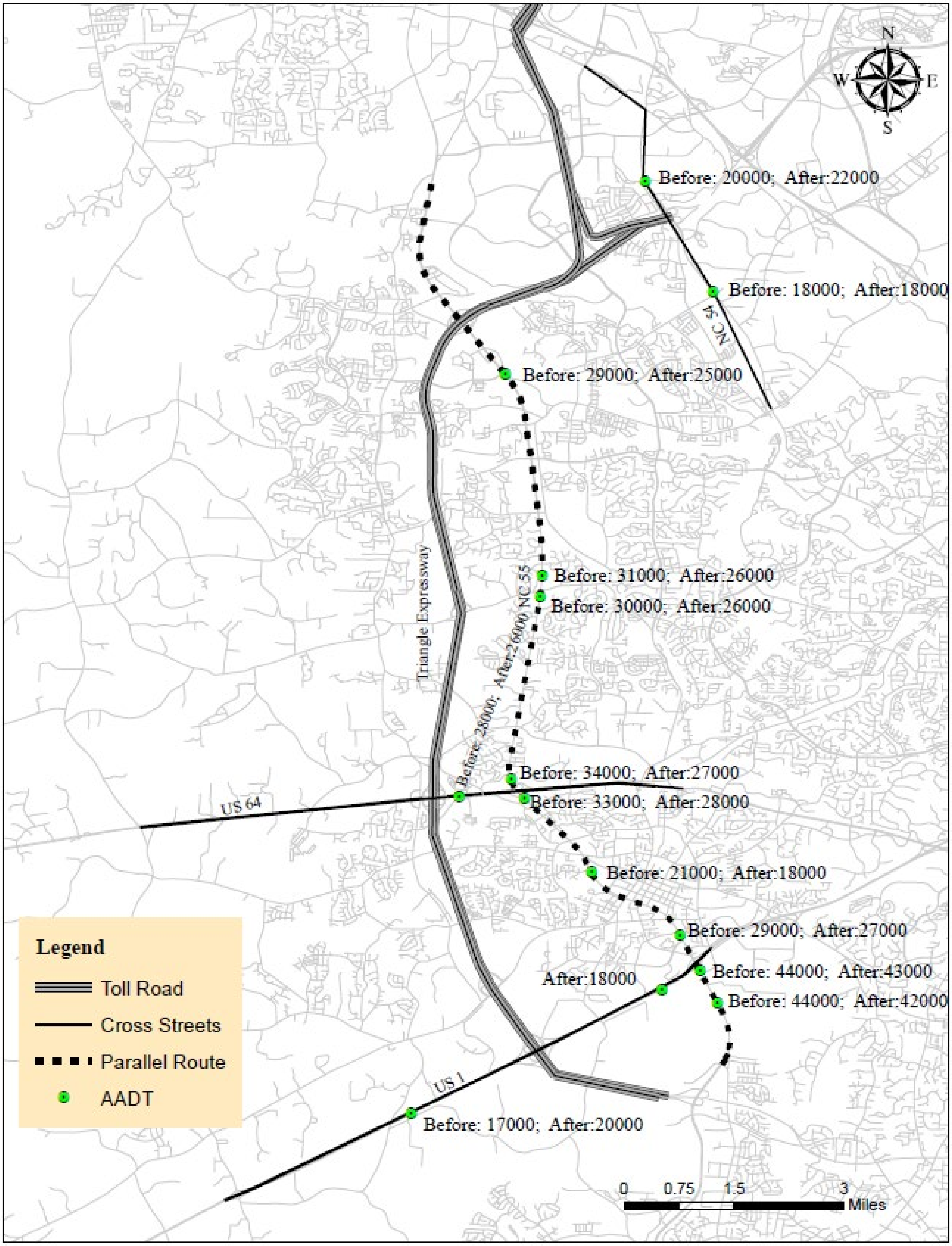

Figure 6. AADT Within the Vicinity of Toll Road

ANALYSIS SUMMARY

This chapter examined the effectiveness of a toll road in reducing congestion and improving travel time reliability of other roads within its vicinity. The effect of the toll road was analyzed for four different scenarios: before construction; during Phase 1 operation; during Phase 2 operation; and after opening the toll road for complete service (Phase 3). The travel time measure ATT, and the travel time reliability measures PT, BT, and BTI, were computed for each link, categorized by day-of-the-week and by time-of-the-day. Data corresponding to typical peak hours of weekday traffic and weekend traffic were identified for the analysis. One of the main findings of this study is that different measures of reliability behave differently for the same link for the same analysis period. As BT and BTI can depict the actual effect of the toll facility on each selected link within the vicinity of toll road, these are good travel time reliability measures to assess the effect of large-scale transportation projects, such as toll roads. The before-after comparison of traffic volume showed a notable reduction in traffic volume along the parallel route. This result is in accordance with the Triangle Expressway project's purpose, which was to mitigate congestion on the parallel route (NC 55).

VI. TRAVEL TIME-BASED PERFORMANCE EVALUATION FOR DIFFERENT YEARS OF TOLLWAY OPERATION

This chapter examines the evolution over time of the effectiveness of toll roads in reducing congestion and improving travel time reliability on the streets within its vicinity. 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 the Triangle Expressway, for the parallel alternate route (NC 55), and for cross-streets, categorized by day-of-the-week and by time-of-the-day. Cumulative distribution functions of travel times were generated for the corridor-level assessment.

LINK-LEVEL ANALYSIS

The entire stretch of the Triangle Expressway, comprised of 34 links, was considered in the analysis. As the Triangle Expressway became fully functional in January 2013, the travel time-based assessment was started from the year 2013. The travel measures ATT, PT, BT, and BTI were also computed for the years 2014, 2015, 2016, and 2017. Counterintuitively, the majority of the links on the toll road showed a trend of improvement in travel time reliability measures over the year of its operation, despite the NCDOT traffic volume interactive map reporting an increase in traffic volume over the years along the entire stretch of the Triangle Expressway. The analysis performed for the toll road for a typical weekday morning peak hour is summarized in Table 8. For each selected link, the ratios between the travel time performance measures for the year, and the same measures for the previous year, were computed. Similarly, to the previous chapter, grey-shaded cells indicate worsening in performance and the degree of change in performance measure was illustrated using red colored data bars. All the selected links are included in Table 8; however, travel time data for some of the links was not available for the year 2013 and 2015.

The travel time performance measure improved on the majority of the links on the toll road from 7:00 a.m. to 8:00 a.m. on a weekday, a typical peak hour for work trips. While considering the ratios of travel time reliability measures along the Triangle Expressway over the year, improvement, as mentioned earlier, is more consistent. Notably, while considering ATT and PT, there is evidence of improvement in the year 2014. For example, for link ID T5S, ratio of ATT 2014 to ATT 2013 is 0.87; a decrease of 13%. Moreover, that trend towards improvement is consistently found on all the other selected links. The decrease in travel time during 2014 can also be observed from the line plot generated using the entire travel time data (Figure 7). This decrease in travel time could be attributed to the increase in speed limit from 60 miles/hour to 70 miles/hour along the Triangle Expressway.

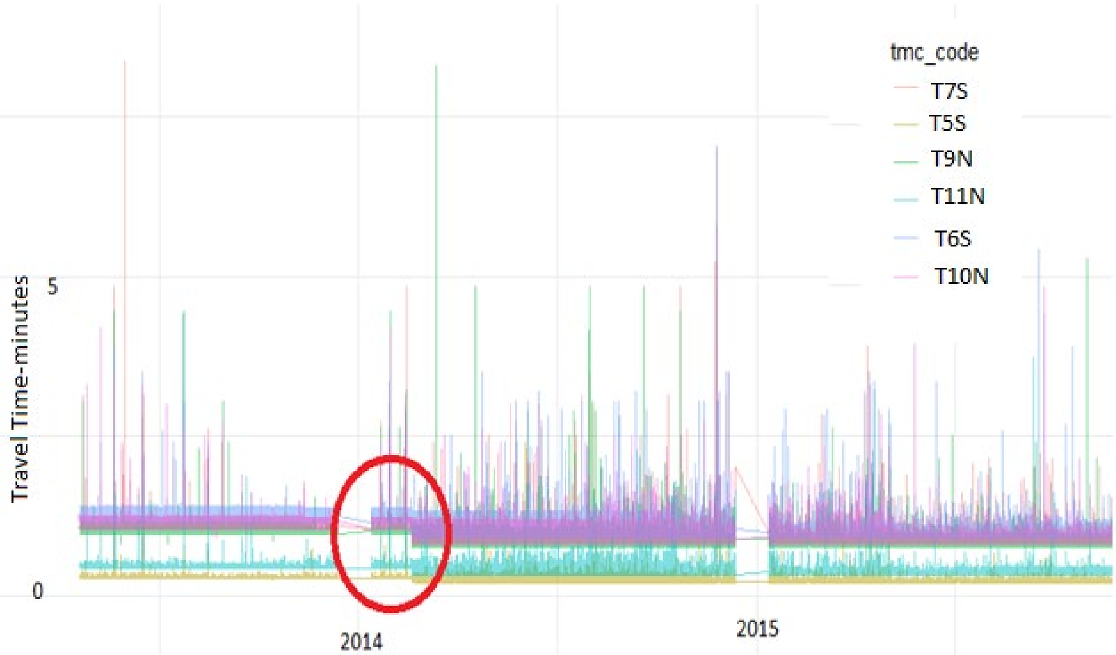

Figure 7. Distribution of Travel Times Along Toll Road

Table 9 summarizes the travel time reliability assessment for the toll road for a typical weekday evening peak hour. Similarly, to the weekday morning peak assessment, travel time reliability measures were improved for 2014 and 2015. However, the reliability worsened in most of the links during 2016 and 2017.

According to the reports from the North Carolina Turnpike Authority (NCTA), the Triangle Expressway construction was originally intended to relieve congestion on NC 55 (parallel road) while improving access to the Research Triangle Park by reducing travel times for motorists residing to the south and east of the region. Therefore, evaluation of travel time variations on the parallel route, over time, is necessary in order to comment on the outcome of this large-scale transportation project. Table 10 summarizes the analysis of link level travel time reliability for a typical weekday peak hour (7:00 a.m. to 8:00 a.m., Wednesday).

The majority of the links showed worsening of ATT, PT, BT, and BTI, over every year of the toll road's operation. As the Triangle Expressway was constructed to relieve congestion on NC 55, this trend of worsening travel time reliability measures on NC 55 over the years does not seem like a positive influence of the toll road unless there is a significant growth in traffic volume. Traffic volume maps of NCDOT showed an increase of 1000 in AADT along the parallel route (NC 55) from 2013 to 2014 and 2014 to 2015. The parcel data for NC 55 and near-vicinity corridors showed it to be a residential zone with many major trip attractions. Moreover, the land use changes over the years indicated growth in residential land use near to the parallel alternate route and the near vicinity corridors. Therefore, it can be considered a plausible explanation for this change in travel time reliability over time. Traffic volumes of the entry and exit ramps connecting Triangle Expressway also showed a major increase over the analysis period.

Table 11 shows the assessment results for the evening peak. Similarly, to the morning peak, the majority of the links showed a clear trend of worsening of travel time reliability over time.

A similar analysis was performed for the major cross-streets, US 64, NC 54 and US 1, for the selected years and summarized in Table 12 and Table 13. The travel time reliability measures for cross-streets links worsened in the year 2014; however, no specific trend was observed during 2015, 2016, and 2017. Also, comparison of AADT in the 2-mile vicinity showed an increase in traffic volume in 2014 and steady trend in the case of 2015, 2016, and 2017.

Table 8. Travel Time Reliability Measures for Toll Road in the Morning Peak Hour (Over Time)

Link	Length	Percentile Change (ATT)				Percentile Change (PT)				Percentile Change (BT)				Percentile Change (BTI)			
		2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
T1S	0.64	-	0.95	1.02	0.98	-	1.00	1.00	0.98	-	2.50	0.80	1.00	-	2.63	0.79	1.02
T2S	1.24	-	0.96	1.00	0.99	-	1.04	1.00	0.97	-	9.00	1.00	0.67	-	9.33	1.00	0.67
T3S	1.15	-	-	0.99	1.00	-	-	0.99	0.98	-	-	1.00	0.75	-	-	1.01	0.75
T4S	0.74	-	-	1.00	0.98	-	-	0.99	0.99	-	-	0.86	1.00	-	-	0.86	1.02
T5S	0.28	0.87	0.96	1.04	1.00	1.06	0.79	0.96	1.00	2.25	0.33	0.33	1.00	2.52	0.35	0.32	1.00
T6S	1.17	0.82	0.98	1.00	1.00	0.89	0.86	0.98	1.00	0.96	0.35	0.75	1.00	1.10	0.35	0.75	1.00
T7S	1.05	0.83	0.98	1.01	1.00	0.89	0.88	0.99	0.98	0.95	0.40	0.75	0.67	1.09	0.41	0.74	0.67
T8S	4.07	-	-	1.01	1.00	-	-	1.00	1.00	-	-	0.76	1.00	-	-	0.75	1.00
T9S	0.34	-	-	1.00	1.00	-	-	1.00	1.00	-	-	1.00	1.00	-	-	1.00	1.00
T10S	2.07	-	-	1.01	1.00	-	-	1.02	0.98	-	-	1.10	0.73	-	-	1.09	0.73
T11S	1.02	-	-	1.01	1.00	-	-	1.00	1.00	-	-	0.86	1.00	-	-	0.85	1.00
T12S	1.85	-	-	1.01	1.00	-	-	1.00	1.00	-	-	0.82	1.00	-	-	0.81	1.00
T13S	0.36	-	-	1.00	1.00	-	-	0.97	1.03	-	-	0.50	2.00	-	-	0.50	2.00
T14S	0.67	-	-	1.00	1.00	-	-	0.97	1.00	-	-	0.71	1.00	-	-	0.71	1.00
T15S	0.72	-	-	0.98	1.02	-	-	0.96	1.00	-	-	0.75	0.83	-	-	0.76	0.82
T16S	1.23	-	-	1.00	1.00	-	-	1.07	0.95	-	-	5.50	0.36	-	-	5.50	0.36
T1N	1.33	-	-	1.00	1.00	-	-	1.00	1.00	-	-	1.00	1.00	-	-	1.00	1.00
T3N	0.56	-	-	1.02	1.00	-	-	1.00	1.00	-	-	0.75	1.00	-	-	0.73	1.00
T4N	0.39	-	-	1.00	1.03	-	-	1.00	1.00	-	-	1.00	0.67	-	-	1.00	0.65
T5N	1.83	-	-	1.00	1.01	-	-	1.00	1.02	-	-	1.00	1.12	-	-	1.00	1.11
T6N	1.01	-	-	1.00	1.01	-	-	1.00	1.00	-	-	1.00	0.83	-	-	1.00	0.82
T7N	2.13	-	-	1.00	1.00	-	-	1.00	1.00	-	-	1.00	1.00	-	-	1.00	1.00
T8N	0.27	-	-	1.00	-	-	-	0.96	-	-	-	0.50	-	-	-	0.50	-
T9N	4.13	-	-	0.99	1.01	-	-	1.00	1.00	-	-	1.36	0.74	-	-	1.38	0.73
T10N	0.97	0.79	0.96	1.00	1.03	0.85	0.91	0.95	1.01	0.88	0.60	0.56	0.80	1.04	0.62	0.56	0.78
T11N	1.05	0.77	0.98	1.00	1.00	0.84	0.89	0.97	1.00	0.86	0.44	0.63	1.00	1.02	0.45	0.63	1.00
T12N	0.44	0.84	0.97	0.97	1.03	1.02	0.79	0.93	1.03	2.00	0.29	0.50	1.00	2.32	0.29	0.51	0.97
T13N	0.66	-	0.98	0.98	1.02	-	1.03	1.02	1.00	-	2.50	1.40	0.86	-	2.54	1.42	0.84
T14N	1.10	-	0.97	0.99	1.01	-	1.00	0.97	1.03	-	1.50	0.78	1.29	-	1.55	0.79	1.27
T15N	1.08	-	0.99	0.98	1.02	-	1.03	0.98	1.02	-	2.00	1.00	1.00	-	2.02	1.02	0.98
T16N	0.82	-	1.04	0.96	1.01	-	1.02	0.98	1.02	-	0.89	1.12	1.11	-	0.85	1.17	1.10

Note: Grey highlighted cells indicate worsening of the travel time reliability measure; red bars indicate the degree of change in travel time reliability over years of toll road operation.

Table 9. Travel Time Reliability Measures for the Toll Road in the Evening Peak Hour (Over Time)

Link	Length	Percentile Change (ATT)				Percentile Change (PT)				Percentile Change (BT)				Percentile Change (BTI)			
		2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
T1S	0.64	-	-	1.00	1.00	-	-	1.08	0.99	-	-	3.70	0.86	-	-	3.70	0.86
T2S	1.24	0.82	0.98	1.00	0.99	0.93	0.86	1.06	0.98	1.33	0.35	1.71	0.92	1.54	0.36	1.71	0.93
T3S	1.15	0.87	0.95	1.03	0.97	0.98	0.79	1.05	0.98	1.44	0.31	1.25	1.00	1.63	0.32	1.22	1.03
T4S	0.74	-	-	1.03	0.95	-	-	1.08	0.94	-	-	1.37	0.91	-	-	1.33	0.96
T5S	0.28	-	-	1.01	1.00	-	-	1.04	0.97	-	-	1.37	0.73	-	-	1.36	0.73
T6S	1.17	-	-	1.00	1.00	-	-	1.04	0.98	-	-	1.73	0.84	-	-	1.73	0.84
T7S	1.05	-	-	1.01	0.99	-	-	1.03	1.00	-	-	1.27	1.14	-	-	1.26	1.16
T8S	4.07	-	-	1.02	0.98	-	-	1.04	0.98	-	-	1.20	1.00	-	-	1.18	1.02
T9S	0.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T10S	2.07	0.81	1.00	1.00	0.97	0.91	0.88	1.03	0.97	1.22	0.36	1.37	1.00	1.43	0.36	1.37	1.03
T11S	1.02	0.83	1.00	1.00	1.00	1.00	0.82	1.07	0.93	1.80	0.33	1.67	0.60	2.10	0.33	1.67	0.60
T12S	1.85	-	-	1.02	0.97	-	-	1.00	1.00	-	-	0.80	1.38	-	-	0.79	1.41
T13S	0.36	-	-	1.02	0.97	-	-	1.01	1.01	-	-	1.00	1.43	-	-	0.98	1.47
T14S	0.67	-	-	1.00	0.97	-	-	1.01	1.00	-	-	1.24	1.35	-	-	1.24	1.38
T15S	0.72	-	-	1.01	0.97	-	-	1.06	0.95	-	-	1.83	0.82	-	-	1.81	0.84
T16S	1.23	-	-	1.02	0.97	-	-	0.98	0.97	-	-	0.70	1.00	-	-	0.69	1.03
T1N	1.33	-	-	1.00	0.96	-	-	1.08	0.93	-	-	2.00	0.70	-	-	2.00	0.73
T3N	0.56	-	-	-	1.00	-	-	-	1.00	-	-	-	1.00	-	-	-	1.00
T4N	0.39	0.81	0.99	1.01	0.98	1.00	0.83	1.00	0.98	2.06	0.33	0.91	1.00	2.41	0.34	0.90	1.02
T5N	1.83	-	-	1.00	0.97	-	-	0.99	1.03	-	-	0.90	1.67	-	-	0.90	1.72
T6N	1.01	-	-	1.00	0.98	-	-	1.03	1.00	-	-	2.00	1.25	-	-	2.00	1.27
T7N	2.13	-	-	1.00	0.97	-	-	1.00	1.00	-	-	1.00	1.50	-	-	1.00	1.55
T8N	0.27	-	-	1.00	0.98	-	-	1.03	0.99	-	-	1.60	1.13	-	-	1.60	1.15
T9N	4.13	-	-	1.03	0.97	-	-	1.03	1.00	-	-	1.00	1.33	-	-	0.97	1.38
T10N	0.97	-	-	1.00	0.97	-	-	1.01	0.99	-	-	1.17	1.14	-	-	1.17	1.18
T11N	1.05	0.82	0.97	1.02	0.97	0.92	0.82	1.05	0.98	1.19	0.28	1.43	1.10	1.37	0.29	1.40	1.14
T12N	0.44	-	-	1.03	0.97	-	-	1.07	0.98	-	-	1.57	1.09	-	-	1.52	1.13
T13N	0.66	-	-	1.01	0.99	-	-	1.00	1.00	-	-	0.88	1.14	-	-	0.86	1.16
T14N	1.10	-	-	1.05	0.96	-	-	1.04	1.00	-	-	1.00	1.50	-	-	0.96	1.57
T15N	1.08	-	-	1.02	0.98	-	-	1.24	0.83	-	-	4.33	0.35	-	-	4.23	0.35
T16N	0.82	-	-	1.00	1.00	-	-	1.03	0.97	-	-	1.33	0.75	-	-	1.33	0.75

Note: Grey highlighted cells indicate worsening of the travel time reliability measure; red bars indicate the degree of change in travel time reliability over years of toll road operation.

Table 10. Travel Time Reliability Measures for the Parallel Route in the Morning Peak Hour (Over Time)

Length	Percentile Change (ATT)				Percentile Change (PT)				Percentile Change (BT)				Percentile Change (BTI)			
	2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
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
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
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
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
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
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
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
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
0.76	1.04	1.05	1.06	1.03	1.15	1.27	1.16	1.12	1.93	2.17	1.36	1.26	1.85	2.08	1.29	1.22
1.37	1.00	1.09	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
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
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
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
0.80	1.12	1.00	0.97	1.03	1.10	1.07	1.00	1.08	1.03	1.33	1.08	1.19	0.92	1.33	1.11	1.15
1.86	1.07	1.02	0.99	0.98	1.08	1.06	1.03	0.95	1.16	1.28	1.18	0.83	1.09	1.26	1.19	0.84
2.26	1.13	0.98	0.99	1.02	1.34	0.92	1.03	1.10	3.25	0.72	1.17	1.39	2.87	0.73	1.18	1.37

Note: Grey highlighted cells indicate worsening of the travel time reliability measure; red bars indicate the degree of change in travel time reliability over years of toll road operation.

Table 11. Travel Time Reliability Measures for the Parallel Route in the Evening Peak Hour (Over Time)

Link	Length	Percentile Change (ATT)				Percentile Change (PT)				Percentile Change (BT)				Percentile Change (BTI)			
		2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
P3S	1.45	1.17	1.17	1.01	1.17	1.57	1.17	1.00	1.13	3.64	1.17	0.98	1.05	3.10	1.00	0.97	0.90
P4S	2.26	1.10	1.07	0.98	1.04	1.21	1.13	1.00	1.07	2.15	1.44	1.08	1.15	1.95	1.35	1.11	1.11
P5S	1.86	1.03	1.01	0.97	1.02	1.07	1.08	0.93	1.08	1.75	1.61	0.71	1.52	1.71	1.58	0.73	1.50
P6S	0.82	1.11	1.06	1.01	0.93	1.12	1.27	1.00	0.84	1.21	2.34	0.98	0.62	1.09	2.21	0.97	0.66
P7S	1.02	1.13	1.11	1.09	1.19	1.08	1.26	1.27	1.07	0.92	1.99	1.74	0.88	0.81	1.80	1.59	0.74
P8S	0.78	1.24	1.07	1.32	0.89	1.37	1.23	1.62	0.73	1.88	1.65	2.12	0.56	1.51	1.54	1.60	0.63
P9S	1.18	1.06	1.01	1.00	1.07	1.13	1.00	1.00	1.14	–	–	0.99	1.37		0.98	0.99	1.28
P10S	1.40	1.15	0.95	0.98	0.92	1.11	1.00	1.00	0.86	1.06	1.07	1.03	0.78	0.93	1.13	1.06	0.84
P1N	0.76	1.09	1.02	1.00	1.06	1.11	1.21	0.94	1.15	1.34	2.83	0.74	1.53	1.23	2.78	0.74	1.44
P2N	1.37	1.17	0.99	0.97	1.01	1.29	1.00	1.00	0.96	1.82	1.02	1.07	0.85	1.56	1.03	1.11	0.84
P3N	1.18	1.11	1.03	1.16	1.00	1.16	1.12	1.31	0.93	1.43	1.48	1.73	0.79	1.29	1.44	1.49	0.79
P4N	0.78	1.20	0.99	1.05	0.97	1.33	1.09	1.10	0.91	2.38	1.50	1.22	0.78	1.99	1.52	1.16	0.81
P5N	1.02	1.16	1.07	1.00	1.16	1.29	1.26	1.00	1.12	2.23	1.99	1.00	1.03	1.91	1.86	1.00	0.89
P6N	0.80	1.09	1.00	1.04	1.03	1.17	1.03	1.07	1.08	1.54	1.14	1.19	1.22	1.40	1.15	1.14	1.19
P7N	1.86	1.12	1.02	1.04	1.01	1.12	1.14	1.04	1.03	1.15	1.78	1.02	1.11	1.03	1.75	0.98	1.10
P8N	2.26	1.10	1.02	0.99	1.02	1.14	1.09	1.00	1.00	1.37	1.46	1.04	0.92	1.24	1.43	1.06	0.91

Note: Grey highlighted cells indicate worsening of the travel time reliability measure; red bars indicate the degree of change in travel time reliability over years of toll road operation.

Table 12. Travel Time Reliability Measures for Cross-Streets in the Morning Peak Hour (Over Time)

Link	Length	Percentile Change (ATT)				Percentile Change (PT)				Percentile Change (BT)				Percentile Change (BTI)			
		2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
C1S	0.90	1.07	1.08	0.96	1.01	1.29	1.17	0.86	1.22	3.70	1.44	0.62	2.01	3.45	1.34	0.65	2.00
C2S	0.92	1.14	1.09	0.97	1.07	1.26	1.22	1.10	1.00	2.40	1.82	1.44	0.87	2.10	1.67	1.48	0.82
C4S	1.72	1.41	0.91	1.04	1.00	1.88	0.85	1.05	0.95	4.91	0.75	1.09	0.86	3.49	0.83	1.05	0.86
C5S	1.69	1.19	0.94	1.04	1.01	1.35	0.96	1.08	1.00	3.71	1.10	1.26	0.98	3.12	1.17	1.22	0.98
C1N	1.69	1.19	0.95	1.02	1.01	1.30	0.96	1.04	1.05	2.12	1.01	1.12	1.15	1.79	1.07	1.10	1.14
C2N	1.73	1.20	0.99	1.04	0.95	1.40	1.00	1.04	0.96	4.46	1.03	1.06	1.01	3.73	1.04	1.03	1.07
C4N	0.92	1.26	1.03	1.00	0.98	1.94	1.00	0.89	1.00	8.73	0.95	0.71	1.04	6.94	0.92	0.71	1.07
C5N	0.90	1.21	0.98	1.01	0.99	1.59	0.85	1.04	1.04	4.37	0.56	1.13	1.21	3.61	0.57	1.11	1.22
C3E	1.62	1.01	1.00	1.13	0.91	0.98	1.02	1.16	0.97	0.63	1.42	1.62	1.49	0.62	1.42	1.43	1.64
C5E	0.45	1.05	1.09	1.33	1.04	1.49	1.28	1.94	1.06	11.04	1.69	2.75	1.08	10.48	1.56	2.06	1.04
C1W	0.50	1.01	0.99	1.00	1.01	1.04	1.00	0.98	0.98	1.64	1.10	0.77	0.60	1.62	1.11	0.77	0.60
C3W	2.93	1.01	0.98	0.99	1.00	1.00	0.99	0.98	1.00	0.89	1.07	0.87	0.93	0.88	1.09	0.87	0.93
C7E	0.38	1.00	0.98	0.99	1.01	1.00	0.98	0.98	1.00	1.05	0.88	0.81	0.87	1.05	0.90	0.82	0.86
C9E	0.13	1.01	0.97	1.00	1.01	1.07	0.88	1.00	1.00	1.50	0.38	0.98	0.90	1.48	0.39	0.98	0.90
C10E	0.50	1.01	1.01	0.99	1.01	1.04	1.00	0.98	1.00	1.57	0.85	0.86	0.84	1.56	0.84	0.87	0.83
C11E	0.85	1.03	1.00	1.00	1.01	1.05	1.00	0.96	1.02	1.43	1.01	0.61	1.19	1.39	1.01	0.61	1.18
C7W	0.83	1.01	1.02	1.01	0.99	1.03	1.02	0.98	0.99	1.53	1.00	0.63	0.99	1.52	0.98	0.63	1.00
C8W	0.33	1.03	1.01	1.00	0.99	1.06	0.97	0.97	1.00	1.47	0.67	0.62	1.11	1.43	0.66	0.62	1.12
C9W	0.34	0.99	0.99	1.02	1.00	1.00	0.97	1.00	1.00	1.12	0.82	0.84	1.04	1.13	0.83	0.83	1.05
C11W	3.15	0.99	1.01	1.04	1.00	1.04	1.02	1.06	1.02	1.67	1.06	1.25	1.18	1.68	1.05	1.20	1.18

Note: Grey highlighted cells indicate worsening of the travel time reliability measure; red bars indicate the degree of change in travel time reliability over years of toll road operation.

Table 13. Travel Time Reliability Measures for Cross-Streets in the Evening Peak Hour (Over Time)

Link	Length	Percentile Change (ATT)				Percentile Change (PT)				Percentile Change (BT)				Percentile Change (BTI)			
		2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
C1S	0.90	1.09	1.15	1.14	0.85	1.22	1.23	1.69	0.62	2.03	1.49	3.11	0.41	1.86	1.30	2.73	0.48
C2S	0.92	1.24	1.10	1.00	0.98	1.60	1.11	1.13	0.94	5.19	1.14	1.42	0.87	4.18	1.04	1.42	0.89
C4S	1.72	1.46	0.98	1.07	1.19	1.50	1.17	1.09	1.00	1.59	1.57	1.13	0.75	1.08	1.60	1.06	0.63
C5S	1.69	1.39	1.20	1.03	1.18	1.25	1.20	1.00	1.11	1.08	1.20	0.96	0.98	0.78	1.00	0.93	0.83
C1N	1.69	1.28	1.18	1.32	0.81	1.45	1.54	1.45	0.64	2.30	2.57	1.60	0.46	1.79	2.18	1.21	0.57
C2N	1.73	1.14	1.01	1.04	1.00	1.26	1.04	1.08	1.00	2.67	1.16	1.28	0.99	2.35	1.14	1.23	0.99
C4N	0.92	1.25	1.03	1.20	1.10	1.58	1.19	1.23	1.08	6.63	1.66	1.29	1.05	5.29	1.62	1.08	0.96
C5N	0.90	1.30	0.91	1.02	0.97	1.75	0.83	1.09	1.00	5.55	0.67	1.28	1.06	4.26	0.74	1.25	1.09
C3E	1.62	0.99	0.99	1.01	1.00	0.98	1.02	1.00	1.00	0.78	1.64	0.91	0.97	0.78	1.65	0.90	0.96
C5E	0.45	1.01	0.97	1.01	1.00	1.00	0.95	1.00	1.00	0.94	0.76	0.88	0.98	0.93	0.78	0.87	0.97
C1W	0.50	1.04	0.97	1.00	1.00	1.15	0.94	0.96	1.00	2.75	0.79	0.69	0.95	2.64	0.82	0.70	0.95
C3W	2.93	1.00	0.96	1.00	1.00	1.01	0.96	1.00	1.00	1.26	0.86	1.05	1.00	1.26	0.89	1.05	1.00
C7E	0.38	0.99	0.97	1.01	0.99	1.02	0.98	0.98	1.00	1.78	1.08	0.65	1.17	1.81	1.11	0.65	1.18
C9E	0.13	1.00	0.96	1.03	0.98	1.00	0.93	1.00	1.00	0.99	0.69	0.68	1.26	0.99	0.71	0.66	1.28
C10E	0.50	1.01	0.99	1.00	1.00	1.02	0.98	1.00	1.00	1.18	0.90	0.94	1.01	1.17	0.91	0.94	1.01
C11E	0.85	1.02	1.00	1.01	1.00	1.03	1.02	0.98	1.00	1.28	1.33	0.65	1.00	1.26	1.33	0.65	1.00
C7W	0.83	1.02	1.03	1.00	0.99	1.05	1.07	0.96	1.00	1.55	1.47	0.61	1.12	1.52	1.43	0.61	1.13
C8W	0.33	1.01	1.02	0.99	1.00	1.03	1.03	0.97	1.00	1.34	1.13	0.75	0.96	1.33	1.11	0.75	0.96
C9W	0.34	1.00	0.99	1.00	1.01	1.05	0.90	1.00	1.00	1.40	0.46	0.95	0.91	1.40	0.46	0.95	0.90
C11W	3.15	0.99	1.03	1.02	1.03	1.00	1.10	1.00	1.07	1.09	1.77	0.89	1.28	1.11	1.72	0.87	1.25

Note: Grey highlighted cells indicate worsening of the travel time reliability measure; red bars indicate the degree of change in travel time reliability over years of toll road operation.

CORRIDOR-LEVEL ASSESSMENT

The outcomes from the link-level analysis indicate a clear trend of improvement on the majority of the selected links along the toll road for the years 2013 and 2014, and of worsening for the years 2016 and 2017. Similarly, a trend of worsening travel time reliability for the parallel street was also observed in the link- level assessment. To quantify overall improvement in travel time performance measure, a corridor-level assessment, separately for the toll road, parallel alternate route, and cross-streets, was performed. Data normalization was carried out by dividing the travel time with the length of each link. The cumulative distribution functions of per-mile travel times for the Triangle Expressway is summarized in Figure 8.

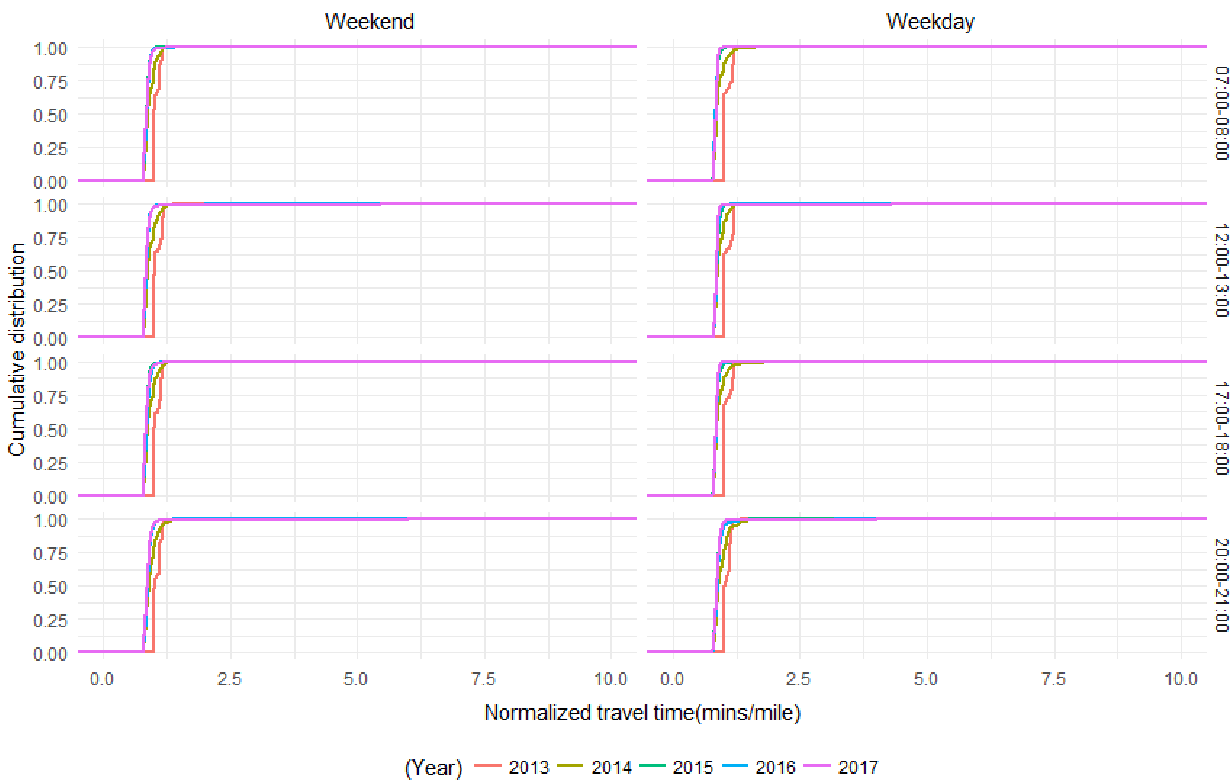

Figure 8. Cumulative Distribution of Travel Times on the Toll Road (Over Time)

From Figure 8, it can be seen that there exists a disparity in the cumulative distribution of 2013 travel times compared to other years. The sudden change in speed limit could be the main reason behind this shift in travel time distribution from the year 2013. Over the year, stabilization of travel time distributions was observed. The variations in travel time is found to be very low from the distribution. The travel time pattern remains the same, even after the increase in traffic volume in the Triangle Expressway. As a general notion, the increase in traffic volume will increase the travel time in a corridor. However, such a result is not observed in the case of Triangle Expressway.

The cumulative distribution functions for travel times on the parallel route and on cross-streets provide useful indications of the overall increase in travel time and travel time reliability measures over time. On the parallel route, Figure 9, the travel time increased, i.e. worsened, over the years. This trend is clearest during peak hours, 7:00 a.m. to 8:00 a.m. and 5:00 p.m. to 6:00 p.m., on typical weekdays, with a shift being observed every year. The Research Triangle is one of the dominant locations for employment in the study region. Therefore, parallel alternate route (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 the NC 55 corridor is a major residential zone, the peak hour demand for driving could be one major factor behind such an increase in travel times.

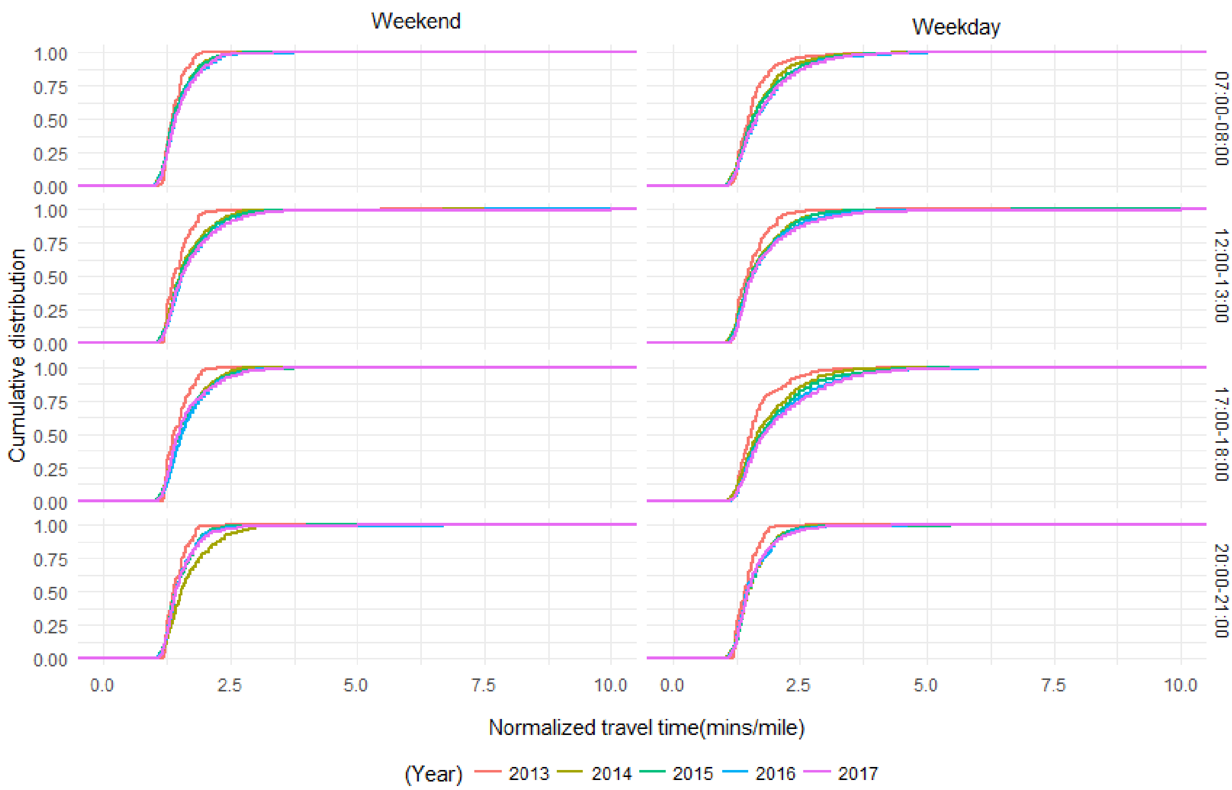

Figure 9. Cumulative Distribution of Travel Times for the Parallel Route (Over Time)

A similar analysis was performed for the cross-streets (US 64, NC 54, and US 1). Figure 10 summarizes the results. It is observed that travel time distributions follow a similar trend of increase on cross-streets, after each year of operation of the Triangle Expressway, with the trend stabilizing by 2016 and 2017. In general, the mean travel time is stable at 1.5–2.5 minutes/mile in all the selected peak hours in different years of toll road operation. It can also be seen that there is no change in distribution till the second quartile (75 percentile), beyond 75%, there exists a clear shift in distribution compared to the year 2013.

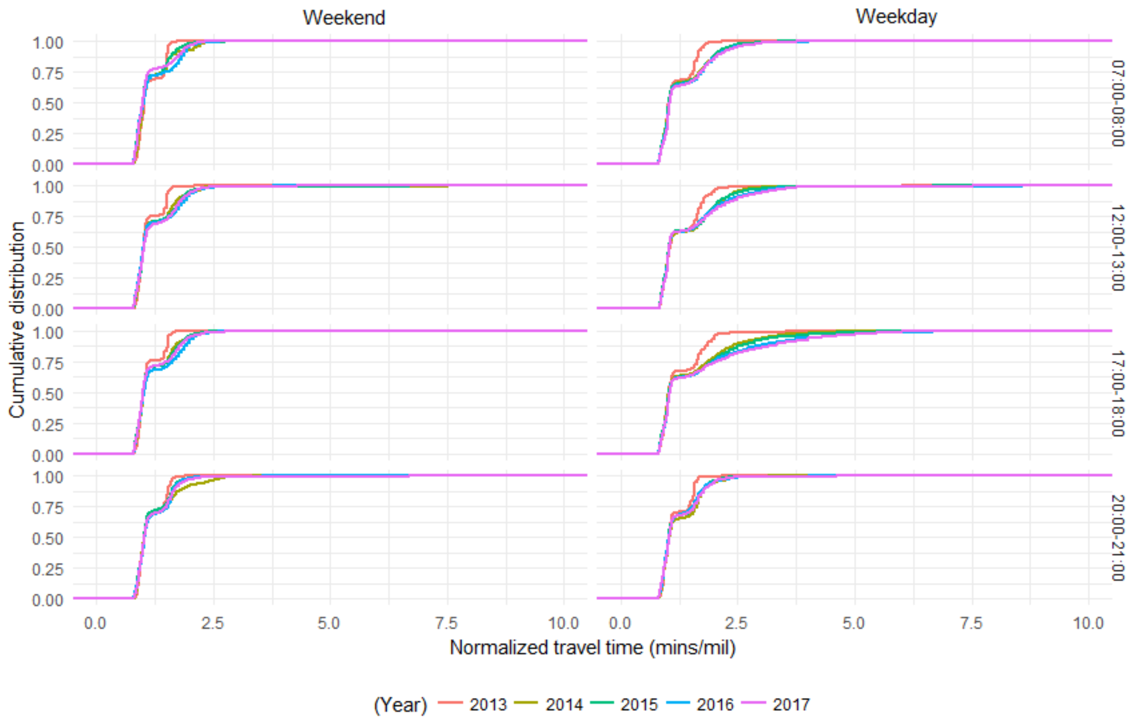

Figure 10. Cumulative Distribution of Travel Times for Cross-Streets (Over Time)

To check the statistical significance of these changes in travel time and travel time reliability performance measures (ATT, PT, BT, and BTI), a one-tail paired t-test was performed at a 95% confidence level. The null hypothesis is 'H0: Travel time reliability measure did not significantly differ from one year to the next'. The alternative hypothesis is 'H1: The travel time reliability measure decreased (i.e., improved) from one year to the next. Table 14 shows the significance test results for the toll road, parallel road; and cross-streets. In the case of toll road, there exists a statistically significant improvement in ATT and PT at the 95% confidence level during 2014. However, BT and BTI indicate a decrease in performance during the initial years after opening the toll road for service.

Table 14. Paired T-Test Results - Over the Time

Time period	ATT				PT				BT				BTI			
	1–2	2–3	3–4	4–5	1–2	2–3	3–4	4–5	1–2	2–3	3–4	4–5	1–2	2–3	3–4	4–5
Toll Road – p-values																
7:00 a.m. – 8:00 a.m. Weekday	<0.01	<0.01	0.46	0.02	0.02	0.02	0.10	0.26	<0.01	0.08	0.13	0.02	<0.01	0.05	0.01	0.03
12:00 p.m. – 1:00 p.m. Weekday	<0.01	<0.01	0.15	0.01	0.01	0.02	<0.01	<0.01	0.29	0.05	<0.01	0.01	<0.01	0.03	<0.01	0.01
5:00 p.m. – 6:00 p.m. Weekday	<0.01	0.06	0.33	0.02	0.01	0.05	0.39	0.33	0.01	0.07	0.38	0.27	<0.01	0.05	0.21	0.36
8:00 p.m. – 9:00 p.m. Weekday	0.01	0.35	0.04	<0.01	0.23	0.08	0.02	0.01	<0.01	0.06	0.03	0.17	<0.01	0.05	0.03	0.08
7:00 a.m. – 8:00 a.m. Weekend	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.04	<0.01	<0.01	<0.01	0.06	<0.01	<0.01	0.01	0.04
12:00 p.m. – 1:00 p.m. Weekend	<0.01	0.01	0.45	<0.01	0.06	<0.01	0.02	0.19	<0.01	<0.01	0.03	0.35	<0.01	<0.01	0.02	0.48
5:00 p.m. – 6:00 p.m. Weekend	<0.01	0.03	0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.37	0.46
8:00 p.m. – 9:00 p.m. Weekend	<0.01	0.04	0.17	0.36	<0.01	<0.01	0.28	0.10	0.04	0.01	0.34	1.70	0.05	<0.01	0.36	1.70
Parallel Route																
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	0.35
5:00 p.m. – 6:00 p.m. Weekday	<0.01	0.01	0.09	0.44	<0.01	<0.01	0.03	0.22	<0.01	<0.01	0.02	0.07	0.02	<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	0.02	0.46
7:00 a.m. – 8:00 a.m. Weekend	<0.01	0.34	<0.01	0.20	<0.01	0.42	0.10	0.42	<0.01	0.46	0.31	0.50	<0.01	0.47	0.34	0.39
12:00 p.m. – 1:00 p.m. Weekend	<0.01	0.06	<0.01	0.05	<0.01	<0.01	0.05	0.14	<0.01	<0.01	0.30	0.41	<0.01	<0.01	0.47	0.34
5:00 p.m. – 6:00 p.m. Weekend	<0.01	0.06	<0.01	0.05	<0.01	<0.01	0.05	0.14	<0.01	<0.01	0.30	0.41	<0.01	<0.01	0.47	0.34
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	0.01	0.15	<0.01	0.01	0.01	0.20
Cross-Street																
7:00 a.m. – 8:00 a.m. Weekday	<0.01	0.42	0.06	0.49	<0.01	0.07	0.16	0.13	<0.01	0.50	0.21	0.12	<0.01	0.42	0.22	0.13
12:00 p.m. – 1:00 p.m. Weekday	<0.01	0.24	0.16	0.11	<0.01	0.05	0.24	0.12	<0.01	0.03	0.35	0.13	<0.01	0.06	0.42	0.22
5:00 p.m. – 6:00 p.m. Weekday	<0.01	0.07	0.02	0.34	0.03	0.03	0.02	0.15	<0.01	0.03	0.03	0.06	<0.01	0.06	0.10	0.04
8:00 p.m. – 9:00 p.m. Weekday	<0.01	0.07	0.13	0.34	<0.01	0.26	0.13	0.34	<0.01	0.40	0.07	0.21	<0.01	0.50	0.08	0.24
7:00 a.m. – 8:00 a.m. Weekend	0.02	0.09	0.02	0.12	<0.01	0.45	0.40	0.04	<0.01	0.18	0.14	0.06	<0.01	0.08	0.08	0.09
12:00 p.m. – 1:00 p.m. Weekend	<0.01	0.03	0.15	0.27	<0.01	0.29	0.07	0.27	<0.01	0.28	0.07	0.16	<0.01	0.16	0.15	0.07
5:00 p.m. – 6:00 p.m. Weekend	<0.01	0.20	<0.01	0.13	<0.01	0.20	0.06	0.46	<0.01	0.21	0.18	0.40	<0.01	0.23	0.16	0.44
8:00 p.m. – 9:00 p.m. Weekend	0.02	0.11	0.25	0.31	<0.01	0.29	0.13	0.36	<0.01	0.40	0.17	0.40	<0.01	0.40	0.17	0.20

Note 1: Highlighted: Worsening at 95% CL

Note 2: 1–2: 2013–2014; 2–3: 2014–2015; 3–4: 2015–2016; 4–5: 2016–2017

The paired t-test results for the parallel street also showed a trend of increase in travel time reliability measures, with statistical significance at the 95% confidence level in 2013 and 2014. The trend follows the same pattern for the parallel road till the year 2017.

ANALYSIS SUMMARY

This chapter examined the effectiveness of toll roads in reducing congestion and improving travel time reliability on the streets within its vicinity, over the years of its operation. The spatial and temporal variations were analyzed in the travel time cumulative distribution functions for the toll road, the parallel alternate route, and the near-vicinity cross-streets (within a 2-mile buffer zone around the toll road). The results indicated that even though there was an improvement in travel time immediately after the speed limit change in 2014, the travel time reliability worsened along the Triangle Expressway. Over time, the reliability measures BT and BTI showed gradual improvement. The parallel route reliability worsened significantly during the analysis period, while the travel time reliability of cross-streets showed a consistent trend. The stabilization of travel time distributions and the reliability measures in 2017 are good indicators, suggesting that further reduction in performance measures may not be expected on the near vicinity corridors.

VII. CONCLUSIONS

This research presents an assessment 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 and travel time reliability of the toll road and other nearby links was analyzed for different phases of toll road construction and for different years of its operation. The Average Travel Time (ATT), the 95th percentile travel time (PT), the Buffer Time (BT), and the Buffer Time Index (BTI) were computed for each link, categorized by day-of-the-week and by time-of-the-day. Data corresponding to typical peak hours of weekday traffic and weekend traffic was identified for the analysis.

The findings indicate that the Triangle Expressway showed a positive trend in reliability over the years of its operation, although a sudden decrease in reliability was observed in 2014, due to the change in speed limit along the toll road. A significant increase in AADT was also reported along the toll road during the same period of analysis. However, the increase in traffic volume does not worsen the travel time and travel time reliability on the Triangle Expressway. The distinguishing capability of expressways in managing higher traffic volume is evident from the analysis.

The Triangle Expressway project's 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 along the Triangle Expressway can be considered as a positive result, as the majority of new traffic is attracted to the more reliable toll road, keeping the alternative free route from becoming as congested as it might otherwise. The stabilization of travel time distributions and the reliability measures in 2017 are good indicators, suggesting that further reduction in performance measures may not be seen on the near vicinity corridors.

The effects of large-scale transportation projects vary spatially and temporally. The cross-streets analyzed in this research substantiated the geospatial and temporal variation of travel times and travel time reliability during different phases of operation. The findings from analysis of travel time distributions and the statistical tests revealed no change in travel time reliability measures on cross-street considered links during the analysis years, however, other than the major change in 2014 compared to 2013.

The travel time distribution and the reliability analysis corresponding to the toll road, parallel alternate route, and the cross-streets for the weekday and weekend (majority of the selected time intervals) all depicted similar patterns over the years. Consideration of individual characteristics, household characteristics, type of vehicle used, and trip purpose may provide vital insights into the weekday-weekend travel time comparison. Conducting in-depth analysis of land use, socio-economic factors, and traffic volume along the project corridor and the near-vicinity corridor would further improve the study applicability. Finally, pricing-elated aspects of the Triangle Expressway were not included in this research but could provide valuable insight.

A systematic framework for the assessment of large-scale transportation projects such as toll roads, conducted over years, of its operation, is exemplified in this research.

Considering the change in land use patterns and traffic volumes after the implementation of the toll road may provide a better picture pertaining to long-term transportation project outcomes and its spatial impact.

ABBREVIATIONS AND ACRONYMS

AADT	Annual Average Daily Traffic
ATT	Average Travel Time
BT	Buffer Time
BTI	Buffer Time Index
DOW	Day-Of-the-Week
PT	Planning Time
PTI	Planning Time Index
RITIS	Regional Integrated Transportation Information System
RTDM	Regional Travel Demand Model
TMC	Traffic Messaging Channel
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled

ENDNOTES

1. Schrank, D., B. Eisele, T. Lomax, and J. Bak."2015 Urban Mobility Scorecard." The Texas A&M University, 2015.

2. North Caroline Department of Transportation," Triangle Expressway." North Carolina Department of Transportation, https://www.ncdot.gov/divisions/turnpike/turnpike-projects/Pages/triangle-expressway.aspx.

3. de Palma, A., and R. Lindsey. "Traffic Congestion Pricing Methodologies and Technologies". *Transportation Research Part C-Emerging Technologies,* 19, no. 6 (2011): 1377–99; Wang, Y. T., Z. X. Peng, K. M. Wang, X. L. Song, B. Z. Yao, and T. Feng. "Research on Urban Road Congestion Pricing Strategy Considering Carbon Dioxide Emissions". *Sustainability,* 7, no. 8 (2015): 10534–53;Hensher, D. A., and S. M. Puckett. "Congestion and Variable User Charging as an Effective Travel Demand Management Instrument". *Transportation Research Part a-Policy and Practice,* 41, no. 7 (2007): 615–26.

4. de Palma, A., and R. Lindsey. "Traffic Congestion Pricing Methodologies and Technologies". *Transportation Research Part C-Emerging Technologies,* 19, no. 6 (2011): 1377–99; Yang, Hai, and Hai-Jun Huang. *Mathematical and Economic Theory of Road Pricing.* Amsterdam: Elsevier Science, 2005.

5. Jones, Peter, and Arild Hervik. "Restraining Car Traffic in European Cities: An Emerging Role for Road Pricing". *Transportation Research Part A: Policy and Practice,* 26, no. 2 (1992): 133–45; Paulley, N. "Recent Studies on Key Issues in Road Pricing". *Transport Policy,* 9, no. 3 (2002): 175–77.

6. Zheng, N., G. Rerat, and N. Geroliminis. "Time-Dependent Area-Based Pricing for Multimodal Systems with Heterogeneous Users in an Agent-Based Environment". *Transportation Research Part C-Emerging Technologies,* 62 (2016): 133–48.

7. Olszewski, P., and L. T. Xie. "Modelling the Effects of Road Pricing on Traffic in Singapore". *Transportation Research Part a-Policy and Practice,* 39, no. 7–9 (2005): 755–72.

8. Zheng, N., R. A. Waraich, K. W. Axhausen, and N. Geroliminis. "A Dynamic Cordon Pricing Scheme Combining the Macroscopic Fundamental Diagram and an Agent-Based Traffic Model". *Transportation Research Part a-Policy and Practice,* 46, no. 8 (2012): 129303; Simoni, M. D., A. J. Pel, R. A. Waraich, and S. P. Hoogendoorn. "Marginal Cost Congestion Pricing Based on the Network Fundamental Diagram". *Transportation Research Part C-Emerging Technologies,* 56 (2015): 221–38.

9. Odeck, J., and T. Skjeseth. "Assessing Norwegian Toll Roads". *Transportation Quarterly,* 49, no. 2 (1995): 89-98; Naess, P., B. Flyvbjerg, and S. Buhl. "Do Road Planners Produce More 'Honest Numbers' Than Rail Planners? An Analysis of Accuracy in Road-Traffic Forecasts in Cities Versus Peripheral Regions". *Transport Reviews,* 26,

no. 5 (2006): 537-7–55; Li, Zheng, and David A. Hensher. “Toll Roads in Australia: An Overview of Characteristics and Accuracy of Demand Forecasts”. *Transport Reviews,* 30, no. 5 (2010): 541–69.

10. Li, Zheng, and David A. Hensher. “Toll Roads in Australia: An Overview of Characteristics and Accuracy of Demand Forecasts”. *Transport Reviews,* 30, no. 5 (2010): 541–69.

11. Welde, M. “Demand and Operating Cost Forecasting Accuracy for Toll Road Projects”. *Transport Policy,* 18, no. 5 (2011): 765–71.

12. Ibid.

13. Van Wee , B., and P. Rietveld. “Cba: Ex Ante Evaluation of Mega-Projects.” Chap. 269–290 In *International Handbook on Mega-Projects*, 480: Edward Elgar Publishing, 2013; Chi, Sae, Jonathan Bunker, and Melissa Teo. “Measuring Impacts and Risks to the Public of a Privately Operated Toll Road Project by Considering Perspectives in Cost-Benefit Analysis”. *Journal of Transportation Engineering, Part A: Systems,* 143, no. 12 (2017): 04017060.

14. Oh, Jung Eun, Samuel Labi, and Kumares C. Sinha. “Implementation and Evaluation of Self-Financing Highway Pricing Schemes: A Case Study”. *Transportation Research Record,* 1996, no. 1 (2007): 25–33.

15. Anas, Alex, and Robin Lindsey. “Reducing Urban Road Transportation Externalities: Road Pricing in Theory and in Practice”. *Review of Environmental Economics and Policy,* 5, no. 1 (2011): 66–88.

16. Chi, Sae, Jonathan Bunker, and Melissa Teo. “Measuring Impacts and Risks to the Public of a Privately Operated Toll Road Project by Considering Perspectives in Cost-Benefit Analysis”. *Journal of Transportation Engineering, Part A: Systems,* 143, no. 12 (2017): 04017060.

17. DeCorla-Souza, Patrick. “Evaluation of Toll Options with Quick-Response Analysis Tools: Case Study of the Capital Beltway”. *Transportation Research Record,* 1839, no. 1 (2003): 65–73.

18. Forkenbrock, D.J., and G.E. Weisbrod.”Guidebook for Assessing the Social and Economic Effects of Transportation Projects.” 456. Washington, D.C.: Transportation Research Board — National Research Council, 2001.

19. Kalmanje, Sukumar., and K.M. Kockelman. “Variations in Toll Road Impacts: Case Studies from Texas”. *Journal of the Transportation Research Forum,* 48, no. 2 (2009): 5–22.

20. National Academies of Sciences, Engineering, and Medicine 2011.”Evaluation and Performance Measurement of Congestion Pricing Projects.” 694. Washington, 2011.

21. National Academies of Sciences, Engineering, and Medicine 2009.”Real-Time Traveler Information Systems.” Washington, DC, 2009.

22. Forkenbrock, D.J., and G.E. Weisbrod.”Guidebook for Assessing the Social and Economic Effects of Transportation Projects.” 456. Washington, D.C.: Transportation Research Board — National Research Council, 2001.

23. Chen, Chao, Alexander Skabardonis, and Pravin Varaiya. “Travel-Time Reliability as a Measure of Service”. *Transportation Research Record,* 1855, no. 1 (2003): 74–79.

24. chrank, D., and T. Lomax.”The 2002 Urban Mobility Report.” The Texas A&M University System, 2002; McLeod, D. S., L. Elefteriadou, and L. Jin. “Travel Time Reliability as a Performance Measure: Applying Florida’s Predictive Model to an Entire Freeway System”. *ITE Journal-Institute of Transportation Engineers,* 82, no. 11 (2012): 43–47.

25. Travel Time Reliability: Making It There on Time, All the Time.” Federal Highway Administration, https://ops.fhwa.dot.gov/publications/tt_reliability/ttr_report.htm.

26. Wakabayashi, Hiroshi, and Yukimasa Matsumoto. “Comparative Study on Travel Time Reliability Indexes for Highway Users and Operators”. *Journal of Advanced Transportation,* 46, no. 4 (2012): 318–39.

27. Goodin, G. D., M. W. Burris, T. Geiselbrecht, and N. Wood. 2013. Application of a Performance Management Framework for Priced Lanes, Report No: FHWA/TX-13/5-6396-01-1). Texas, USA: Texas A&M Transportation Institute.

28. Pulugurtha, S. S., V.R. Duddu, R. Puvvala, V.R. Thokala, and Md. I. Shah.”Commercial Remote Sensing & Spatial Information (Crs & Si) Technologies Program for Reliable Transportation Systems Planning: Volume 2 - Comparative Evaluation of Travel Time Related Performance Measures.” The University of North Carolina at Charlotte, 2015.

29. Ibid.

30. Pulugurtha, S.S., P. Penmetsa, and V.R. Duddu. “Monetizing Reliability to Evaluate the Impact of Transportation Alternatives “: North Carolina Department of Transportation, 2017.

31. North Carolina Turnpike Authority.”Operations Statistics Report for the Triangle Expressway.” 2017.

32. Sharma, A., V. Ahsani, and S. Rawat.”Evaluation of Opportunities and Challenges of Using Inrix Data for Real-Time Performance Monitoring and Historical Trend Assessment.” Iowa State University, 2017.

33. Lomax, T., S. Turner, and R. Margiotta.”Monitoring Urban Roadways in 2002: Using Archived Operations Data for Reliability and Mobility Measurement “. Washington, DC Texas Transportation Institute, 2004; Lyman, Kate, and Robert L. Bertini. “Using

Travel Time Reliability Measures to Improve Regional Transportation Planning and Operations”. *Transportation Research Record,* 2046, no. 1 (2008): 1–10.

34. Wakabayashi, Hiroshi, and Yukimasa Matsumoto. “Comparative Study on Travel Time Reliability Indexes for Highway Users and Operators”. *Journal of Advanced Transportation,* 46, no. 4 (2012): 318–39.

BIBLIOGRAPHY

Anas, Alex, and Robin Lindsey. “Reducing Urban Road Transportation Externalities: Road Pricing in Theory and in Practice”. *Review of Environmental Economics and Policy,* 5, no. 1 (2011): 66–88.

Chen, Chao, Alexander Skabardonis, and Pravin Varaiya. (2003). “Travel-Time Reliability as a Measure of Service”. *Transportation Research Record,* 1855: 74–79.

Chi, Sae, Jonathan Bunker, and Melissa Teo. (2017). “Measuring Impacts and Risks to the Public of a Privately Operated Toll Road Project by Considering Perspectives in Cost-Benefit Analysis”. *Journal of Transportation Engineering, Part A: Systems,* 143(12): 04017060.

De Palma, A., and R. Lindsey. (2011). “Traffic Congestion Pricing Methodologies and Technologies.” *Transportation Research Part C: Emerging Technologies*. 19: 377–1399.

DeCorla-Souza, Patrick. (2003). “Evaluation of Toll Options with Quick-Response Analysis Tools: Case Study of the Capital Beltway”. *Transportation Research Record,* 1839[24]: 65–73.

Federal Highway Administration. “Travel Time Reliability: Making It There on Time, All the Time.” https://ops.fhwa.dot.gov/publications/tt_reliability/ttr_report.htm.

Forkenbrock, D.J., and G.E. Weisbrod. “Guidebook for Assessing the Social and Economic Effects of Transportation Projects.” *Transportation Research Board — National Research Council*, Washington D.C., 2001.

Ginger, G., B. Mark, G. Tina, and W. Nick. “Application of a Performance Management Framework for Priced Lanes. Texas A&M Transportation Institute, 2013.

Goodin, G. D., M. W. Burris, T. Geiselbrecht, and N. Wood. 2013. Application of a Performance Management Framework for Priced Lanes, Report No: FHWA/TX-13/5-6396-01-1). Texas, USA: Texas A&M Transportation Institute.

Hensher, D. A., and S. M. Puckett. (2007). “Congestion and Variable User Charging as an Effective Travel Demand Management Instrument.” *Transportation Research Part A: Policy and Practice*. 41: 615–626.

Kalmanje, Sukumar., and K.M. Kockelman. (2009). “Variations in Toll Road Impacts: Case Studies from Texas”. *Journal of the Transportation Research Forum,* 48(2): 5–22.

Jones, Peter, and Arild Hervik. (1992). “Restraining Car Traffic in European Cities: An Emerging Role for Road Pricing”. *Transportation Research Part A: Policy and Practice*, 26(2): 133–145.

Li, Zheng, and David A. Hensher. (2010). “Toll Roads in Australia: An Overview of Characteristics and Accuracy of Demand Forecasts”. *Transport Reviews,* 30(5): 541–569.

Lomax, T., S. Turner, and R. Margiotta. “Monitoring Urban Roadways in 2002: Using Archived Operations Data for Reliability and Mobility Measurement.” Texas Transportation Institute, 2004.

Lyman, Kate, and Robert L. Bertini. (2008). “Using Travel Time Reliability Measures to Improve Regional Transportation Planning and Operations”. *Transportation Research Record,* 2046: 1–10.

McLeod, D. S., L. Elefteriadou, and L. Jin. (2012). “Travel Time Reliability as a Performance Measure: Applying Florida’s Predictive Model to an Entire Freeway System”. *ITE Journal-Institute of Transportation Engineers,* 82: 43–47.

Naess, P., B. Flyvbjerg, and S. Buhl. (2006). “Do Road Planners Produce More ‘Honest Numbers’ Than Rail Planners? An Analysis of Accuracy in Road-Traffic Forecasts in Cities Versus Peripheral Regions”. *Transport Reviews,* 26(5): 537–555.

National Academies of Sciences, Engineering, and Medicine 2011.”Evaluation and Performance Measurement of Congestion Pricing Projects.” *Transportation Research Board*, Washington D.C., 2011.

National Academies of Sciences, Engineering, and Medicine 2009.”Real-Time Traveler Information Systems.” Washington, DC, 2009. The National Academies Press. https://doi.org/10.17226/14258.

North Carolina Department of Transportation. “Triangle Expressway.” https://www.ncdot.gov/divisions/turnpike/turnpike-projects/Pages/triangle-expressway.aspx.

North Carolina Turnpike Authority. “Operations Statistics Report for the Triangle Expressway.” 2017. https://www.ncdot.gov/divisions/turnpike/turnpike-projects/Documents/operations-statistics-report-q4-2017.pdf

Odeck, J., and T. Skjeseth. (1995). “Assessing Norwegian Toll Roads”. *Transportation Quarterly,* 49(2): 89–98.

Oh, Jung Eun, Samuel Labi, and Kumares C. Sinha. (2007). “Implementation and Evaluation of Self-Financing Highway Pricing Schemes: A Case Study”. *Transportation Research Record,* 1996: 25–33.

Paulley, N. (2002). “Recent Studies on Key Issues in Road Pricing”. *Transport Policy*, 9(3): 75–177.

Pulugurtha, S. S., V.R. Duddu, R. Puvvala, V.R. Thokala, and Md. I. Shah. “Commercial Remote Sensing & Spatial Information (CRS & SI) Technologies Program for

Reliable Transportation Systems Planning: Volume 2 - Comparative Evaluation of Travel Time Related Performance Measures.” Report No: RITARS-12-H-UNCC-1, sponsored by the United States Department of Transportation, 2015.

Pulugurtha, S.S., P. Penmetsa, and V.R. Duddu. “Monetizing Reliability to Evaluate the Impact of Transportation Alternatives “: North Carolina Department of Transportation, 2017.

Schrank, D., and T. Lomax. (2002). “The 2002 Urban Mobility Report”. College Station, TX: Texas Transportation Institute, Texas.

Sharma, A., V. Ahsani, and S. Rawat. “Evaluation of Opportunities and Challenges of Using INRIX Data for Real-Time Performance Monitoring and Historical Trend Assessment.” Iowa State University, 2017.

Simoni, M. D., A. J. Pel, R. A. Waraich, and S. P. Hoogendoorn. (2015). “Marginal Cost Congestion Pricing Based on the Network Fundamental Diagram”. *Transportation Research Part C-Emerging Technologies*, 56: 221–238.

Van Wee, B., and P. Rietveld. (2013). “Cba: Ex Ante Evaluation of Mega-Projects.” In *International Handbook on Mega-Projects*, Chap. 269–290: Edward Elgar Publishing.

Wakabayashi, Hiroshi, and Yukimasa Matsumoto. (2012). “Comparative Study on Travel Time Reliability Indexes for Highway Users and Operators”. *Journal of Advanced Transportation,* 46(4): 318–39.

Wang, Y., Z. Peng, K. Wang, X. Song, B. Yao, and T. Feng. (2015). “Research on Urban Road Congestion Pricing Strategy Considering Carbon Dioxide Emissions.” *Sustainability.* 7: 10534–10553.

Welde, M. “Demand and Operating Cost Forecasting Accuracy for Toll Road Projects”. *Transport Policy,* 18(5): 765–771.

Yang, Hai, and Hai-Jun Huang. (2005). Mathematical and Economic Theory of Road Pricing. Amsterdam: Elsevier Science.

Zheng, N., G. Rerat, and N. Geroliminis. (2016). “Time-Dependent Area-Based Pricing for Multimodal Systems with Heterogeneous Users in an Agent-Based Environment”. *Transportation Research Part C-Emerging Technologies*, 62: 133–148.

ABOUT THE AUTHORS

SONU MATHEW

Mr. Sonu Mathew is pursuing his Ph.D. in Infrastructure and Environmental Systems at the University of North Carolina at Charlotte. He earned his master's degree from Sardar Vallabhbhai National Institute of Technology, Surat, India. His areas of interest are transportation planning, traffic flow modeling and simulation, and traffic safety.

SRINIVAS S. PULUGURTHA

Dr. Srinivas S. Pulugurtha, P.E., F.ASCE is currently working as Professor & Research Director of the Department of Civil & Environmental Engineering at The University of North Carolina at Charlotte (UNC Charlotte). He is also currently directing the Infrastructure, Design, Environment, and Sustainability (IDEAS) Center on UNC Charlotte campus.

PEER REVIEW

San José State University, of the California State University system, and the MTI Board of Trustees have agreed upon a peer review process required for all research published by MTI. The purpose of the review process is to ensure that the results presented are based upon a professionally acceptable research protocol.