RESEARCH & DEVELOPMENT

Monetizing Reliability to Evaluate the Impact of Transportation Alternatives

Srinivas S. Pulugurtha, Ph.D., P.E.
Praveena Penmetsa, M.Tech.
Venkata R. Duddu, Ph.D.

Infrastructure, Design, Environment, and Sustainability (IDEAS) Center
Department of Civil & Environmental Engineering
The University of North Carolina at Charlotte

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MONETIZING RELIABILITY TO EVALUATE THE IMPACT OF TRANSPORTATION ALTERNATIVES

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By

Srinivas S. Pulugurtha, Ph.D., P.E.
Praveena Penmetsa, M.Tech.
Venkata R. Duddu, Ph.D.

Infrastructure, Design, Environment, and Sustainability (IDEAS) Center
Department of Civil & Environmental Engineering
The University of North Carolina at Charlotte
9201 University City Boulevard
Charlotte, NC 28223-0001

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16. Abstract
The objectives of this research project are: 1) to review various definitions of travel time reliability proposed by researchers and practitioners in the past, 2) to estimate and assess the differences in the performance measures to recommend the most appropriate and viable measures, 3) to define and identify travel time reliability thresholds based on additional costs incurred to motorists, and, 4) to monetize reliability based on the recommended definition to assess the impact of transportation alternatives for use by the North Carolina Department of Transportation (NCDOT). Data gathered through preliminary random general survey followed by focus group survey and final random survey are used to research perceptions of North Carolina participants, recommend travel time reliability thresholds and assess the value of travel time, willingness to pay, value of additional trip time, and the value of buffer time.

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Executive Summary

There has been a paradigm shift in focus from intersection-level to link- or corridor-level performance measures and analysis in recent years. The possibility of capturing extensive, continuous, and dynamic travel time data from private sources such as HERE, INRIX and Tom Tom opened many pragmatic avenues to predict reliability at link-level. Travel time reliability (or index or variability) is considered as the most viable performance measure for link- or corridor-level analysis and evaluation of transportation alternatives. It is expected to be widely used in transportation planning, project prioritization, and allocation of resources. The use of travel time reliability for evaluation of transportation alternatives depends on (1) identifying acceptable definition and quantification of reliability for use by transportation planners, engineers, and system managers, their thresholds indicating levels of performance, and, (2) monetizing reliability to evaluate the impact of transportation alternatives. This research focuses on these aforementioned objectives.

The value of travel time refers to the monetary value travelers place on their travel time or in reducing their travel time. On the other hand, the value of reliability connects the monetary value travelers place on reducing travel time variations. There are a very few studies on the value of reliability compared to the value of travel time, travel time savings or willingness to pay. In general, defining monetary values for reliability is challenging unlike travel time savings and estimated average hourly rates to assess the impact of transportation projects or alternatives. To address this challenge, the data to monetize reliability was collected in three stages, a preliminary random general survey followed by focus group survey and final random survey. The surveys were conducted at various cities, towns and other areas across the state of North Carolina to obtain a geographically distributed sample.

The preliminary random general survey was conducted at seven different cities, towns and other areas across North Carolina. A total of 417 samples were collected through this preliminary random general survey. The questions in this case were aimed to capture participant details (level of education and income) and acceptable tolerance levels for different types of trips (work, school, shopping, social and recreational; by time-of-the-day and day-of-the-week) as well as participants' perception in the selection of a reliable or unreliable route. A few questions in the preliminary random general survey are stated preference choices on evaluating how the participants would react to the hypothetical situations. The data collected through preliminary random general survey was used to compute the value of travel time, willingness to pay and the value of additional trip time (maximum planned buffer time).

Nine focus group meetings were conducted with a total 93 participants. The questionnaire for focus group is different from the preliminary random general survey. Unlike the preliminary random general survey participants, the focus group survey participants were given a 10- to 15-minute presentation explaining the concept of travel time reliability and the need for conducting the research project. Feedback, input on questionnaire and travel time reliability was also encouraged prior to collecting data pertaining to participants' perception or tolerance towards the lack of reliability, how long can they tolerate the lack of reliability (which would influence their planned buffer time) and how many days a month can they tolerate the lack of reliability. The data collected through focus group meetings was used to assess the value of buffer time and wage rate per minute of those who choose the reliable route irrespective of possible travel time savings along the alternate route.

The data collected through focus group meetings do not seem to be a good representation of the North Carolina population. Therefore, another round of random survey using the focus group survey questionnaire was conducted to achieve better results in estimating the value of buffer time. This final random survey was conducted at four different cities, town and other areas across North Carolina. A total of 357 samples were collected through this random general survey.

The computed average travel time and average additional trip time for North Carolina are 23.47 minutes and 10.54 minutes, respectively. The average wage rate is ~$0.51 per minute ($30.54 per hour) for the preliminary random general survey sample. From this sample, the computed generalized value of travel time and generalized value of additional trip time (maximum planned buffer time) for North Carolina are also $0.51 per minute. On an average, the value of willingness to pay to reduce one minute of travel time in North Carolina was estimated equal to $0.11.

While 60.8% of final random survey participants were willing to take an unreliable route with a maximum travel time of 30 minutes, only 25.5% of the same group were willing to take an unreliable route with a maximum travel time of 40 minutes (instead of the reliable route). Similarly, 60.8% of final random participants were willing to take an unreliable route with up to two days of the lack of reliability per month. On the other hand, only 33.8% of the same group of participants were willing to take an unreliable route with up to four days of the lack of reliability per month. The value of buffer time from the focus group survey and the final random general survey was estimated equal to $0.48 and $0.45, respectively. Example scenarios are presented to illustrate the applicability of the results to assess the value of transportation projects and alternatives based on findings from this research.

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Chapter 1. Introduction

Travel demand has progressively increased with the development of modern civilization and need for more travel over the past few decades. The subsequent effects of this increasing travel demand are recurring congestion on limited road network, growing air quality problem, and the lack of safe and a reliable transportation system.

For years, fastest-path from an origin to a destination is assumed to be used by most motorists. These motorists usually plan for some expected delay due to recurring congestion, which is common today in many urban areas. Further, motorists' approach towards trip planning seems to be changing due to fluctuations and uncertainty in traffic conditions. The unexpected or non-recurring congestion due to crashes, inclement weather, construction activity and special events, on a day-to-day basis, contribute mostly to these fluctuations and uncertainty. Therefore, reliability (consistency or dependability in travel time) of a route is playing a more prominent role in departure and route choice decisions among various other travel time performance measures.

Reliability is defined as the probability that a component or system will perform a required function (without failure) for a given period of time when used under stated operating conditions (Ebeling, 1997). The reliability of a link, corridor or the transportation road network, therefore, could be defined as the ability to provide an acceptable level of service (LOS) to the traveler under stated environmental and operational conditions during a given period. Reliability as a performance measure is expected to be widely used in transportation planning, for project prioritization, and for allocation of resources.

There has been a paradigm shift in focus from intersection-level to corridor- and area-level performance measures and analysis in recent years. Further, the possibility of capturing extensive, continuous, and dynamic travel time and/or speed data from private sources such as HERE, INRIX and Tom Tom opened many pragmatic avenues to understand and/or predict reliability of transportation system (Pulugurtha et al., 2015). Identifying and defining acceptable reliability measures, quantifying economic values, and performing analyses are vital to understand the impact of transportation alternatives and make informed decisions.

1.1. Need for the Research

As discussed later in the "Literature Review" chapter, several definitions of reliability were proposed and used in the past. They range from travel time percentiles, to travel time indices and variance based measures.

Williams et al. (2013) evaluated travel time reliability measures using INRIX data for five different corridors (I-40 in NC, I-64 in VA, I-95 in FL, I-95 in DE, PA and NJ, and, I-395 in VA and DC) and found that no single measure appears to be ideal as all the considered performance measures (standard deviation, 80th, 85th, 90th, and 95th percentile travel times, Buffer Time Index - BTI, λ_{skew}, and percent below 40 mph & 50 mph) are correlated to average travel time. Except for BTI, no other measure computed in their study can be used to compare the performance of two different segments with varying characteristics (length, speed limit, traffic volume, etc.).

Pulugurtha et al. (2015; 2016) worked on travel time technologies, performance measures and tools for reliable transportation systems planning. They have used data for about 300 links or traffic message channel (TMC) locations in the Charlotte metropolitan area to compute minimum, average, and maximum travel times, 10th, 15th, 50th, 85th, 90th, and 95th percentile travel times, travel time variability based on 85th, 90th, and 95th percentile travel times, Buffer Time (BT), Planning Time (PT), Travel Time Index (TTI), BTI, Planning Time Index (PTI), λ_{Skew}, and λ_{Var}. Results obtained indicate that using travel time reliability or related indices such as PTI, BTI, TTI, λ_{Skew}, and λ_{Var} may yield different outcomes than travel time or travel time percentile based performance measures. A strong correlation was observed between various travel time, travel time percentile and travel time variation related measures. Likewise, a strong correlation was observed between various travel time reliability or related indices.

The definitions (standardized or non-standardized), thresholds and what works best for North Carolina must be researched to clearly establish and identify suitable performance measures and monetizing methods prior to their large-scale application. Such a task must build upon existing literature and explore applicability for analyses of transportation alternatives.

There are a very few studies on the value of reliability compared to the value of travel time. In general, defining monetary values for reliability is challenging unlike travel time savings and estimated average hourly rates to assess impacts and evaluate transportation alternatives. The probability of reaching a destination within an acceptable range of time that takes no longer than the expected travel time plus a certain acceptable additional trip time is one way of defining reliability (Elefteriadou and Cui, 2005). Buffer time, on the other hand, is the amount of extra time that must be allowed for the motorist to reach their destination on-time, in a high percentage of trips (Elefteriadou and Cui, 2005). It could vary by time-of-the-day, day-of-the-week, trip purpose, and for individuals with different motorist characteristics.

Reliably reaching destination on-time could yield different benefits to different motorists. It not only saves time but also their perception towards the transportation system and their planned buffer time for future trips. On the other hand, not all trips may be of utmost importance to all motorists. Clearly, the expected travel time would be high for some links that are congested for a large portion of the time. Consequently, the variability between the expected and 95th percentile travel time may be small in this case. In such a situation, the facility is considered as reliable, though the links are congested (Elefteriadou and Cui, 2005). However, the variability for non-congested travel times is smaller when compared to congested travel times for a regular facility without continuous congestion (Elefteriadou and Cui, 2005). Motorists may consider and account for these aspects when planning their trip. Collecting such related data through surveys / interviews helps better understand the perceptions, possible impact and accurately monetize reliability as a function of the expected or average travel time and buffer time.

Existing methods to monetize the impact of transportation projects are not applicable to assess transportation alternatives based on reliability. With potential for large-scale implementation in the near future, researching and developing a consistent and acceptable method to monetize reliability to analyze transportation alternatives needs immediate attention.

1.2. Research Objectives

The objectives of this research project, therefore, are:

1) to review various definitions of travel time reliability proposed by researchers and practitioners,
2) to estimate and assess the differences in the performance measures to recommend the most appropriate and viable measures,
3) to define and identify reliability thresholds based on additional costs incurred to motorists, and,

4) to monetize reliability based on the recommended definition to assess the impact of transportation alternatives for use by the North Carolina Department of Transportation (NCDOT).

1.3. Organization of the Report

The remainder of this report is comprised of eight chapters. A review of existing literature on travel time reliability, value of travel time and value of travel time reliability is discussed in Chapter 2. Chapter 3 presents an assessment of reliability performance measures to identify appropriate measures for use by NCDOT. The survey and data collection methodology is discussed in Chapter 4. Results obtained from preliminary random general survey are presented in Chapter 5, while results obtained from focus group survey are presented in Chapter 6. Chapter 7 details results from the final random survey using focus group questionnaire, conducted across the North Carolina. Illustration and applicability of results are discussed in Chapter 8. Conclusions from this research study and scope for future research are presented in Chapter 9.

Chapter 2. Literature Review

Reliability requirements for business trips (freight carriers, shippers, and truckers) vary by situation and business characteristics (Fils, 2012). Therefore, it is important that transportation agencies understand these different user requirements to serve them effectively and efficiently. As pointed out by the Transportation Research Board (TRB):

> "….actions taken by transportation agencies to reduce congestion should effectively improve travel time reliability. To assure the effectiveness of those actions, the user requirements regarding travel time reliability must be understood. Different users of the highway network have different requirements for travel time reliability. Moreover, the requirements of each user depend on the situation. A trucker faced with just-in-time delivery has different travel time reliability requirements than an empty backhaul of a mom-and-pop trucking business. Service level agreements for just-in-time delivery can impose severe penalties for not being on time." (TRB, 2011).

This chapter documents various definitions of reliability from transportation perspective. It also discusses various studies that were conducted on travel time reliability measures, value of travel time, and value of travel time reliability.

2.1. Definitions of Reliability

Turner et al. (1996) in their "Measures of Effectiveness for Major Investment Studies" defined trip time reliability as the range of travel times experienced during many daily trips. The National Cooperative Highway Research Program (NCHRP) Report 398 (1997) defined reliability as the impact of non-recurring congestion on the transportation system. Reliability is also defined as the level of variability between the expected travel time (based on scheduled or average travel time) and the actual travel time experienced by the motorists (California Transportation Plan, 1998; Reynolds and Smith & Hills, Inc., 2000; Jackson, 2000; NCHRP 311, 2002). The Florida Department of Transportation (FDOT) (2000) defined reliability on a highway segment as "the percent of travel that takes no longer than the expected travel time plus a certain acceptable additional time". The American Association of State Highway Transportation Officials

(AASHTO's) freight report (2000) defined reliability as "the percent of on-time performance for a given time schedule."

Lomax et al. (2003) defined reliability as the impact of non-recurring congestion on transportation system. Texas Transportation Institute (TTI)'s Urban Mobility Report (2003) makes a distinction between variability and reliability of travel time. Variability refers to the amount of inconsistency of operating conditions, whereas reliability refers to the level of consistency in transportation service. Shaw (2003) recommended reliability as the operational consistency of a facility over an extended period.

NCHRP 8-36 (2004) reviewed the definition of travel time reliability as a part of the F-SHRP program. The study indicated that travel time reliability can be defined in terms of how travel times vary over time (e.g., hour-to-hour, day-to-day). Tseng et al. (2005) stated that the concept of travel time reliability is related to the experienced randomness in travel time. TranSystems (2005) explored some of the definitions that are recommended for travel time reliability. A common definition for reliability was recommended based on the probability of travel times meeting motorists' expectations. The different definitions of reliability depend on motorists' perspective. In mathematical terms, reliability is the probability that a product or service performs adequately over the interval [0, t].

Emam and Al-Deek (2006) defined travel time reliability as the probability that a trip between the origin and destination is made within a specified time interval. FHWA (2007) defined reliability as the consistency or dependability in travel times, as measured from day-to-day and/or across different times of the day. NCHRP Report 399 (2009) defined travel time reliability as a measure of the variability of travel time. It is stated that reliability can be calculated from the standard deviation of travel time. Tilahun and Levinson (2010) defined reliability in terms of the adherence of a systems' operation to its expected behavior. Elefteriadou and Cui (2013) reviewed various definitions of travel time reliability and stated that they all fall under two main categories: a) operationally-based, and, b) variability-based.

2.2. Travel Time Reliability Measures

For assessing travel time reliability or travel time variation, numerous indices were proposed by the researchers in the past. The Federal Highway Administration (FHWA) recommends five standard measures of travel time reliability: 90^{th} or 95^{th} percentile travel time, TTI, PTI, BTI, and how frequently congestion exceeds some expected threshold. Lomax et al. (2003) grouped the performance measures into three categories: statistical range, buffer time measures, and tardy trip indicators. Statistical measures usually take the form of an average value plus or minus standard deviations (at different confidence levels). After studying various measures, they recommended percent variation, misery index, and BTI for use in transportation applications.

In the 1998 California Transportation Plan, percent variation was considered as a reliability measure. It is expressed as follows.

$$\text{Percent Variation} = \frac{\text{Standard Deviation}}{\text{Average Travel Time}} * 100\% \qquad \text{Eq. 1}$$

Variability index, calculated as a ratio of the difference in the upper and lower 95% confidence intervals between the peak period and the off-peak period, was proposed by Jackson and Albert (2000). van Lint (2005) proposed skew and width of the travel time distributions as relevant indicators for unreliability. These two parameters can also provide reliability maps that can be used in identifying day-of-the-week and time-of-the-day periods in which congestion will likely dissolve. In their study, skew standard deviation was defined as shown in Equation 2.

$$\lambda_{\text{Skew}} = \frac{TT_{90} - TT_{50}}{TT_{50} - TT_{10}} \qquad \text{Eq. 2}$$

NCHRP Report 618 (2008) identified PTI, BTI, percent variation, percent on-time arrival and misery index as reliability performance measures. Margiotta et al. (2008) recommended the same as above but replacing percent variation with skew statistics. Charles (2008) mentioned that current reliability practices are lagging behind the recommended approaches. Two ways to model reliability; using probability of non-failure concept and variability of travel time leading to unexpected delays for motorists, were proposed.

Pu (2011) examined the fundamental causes of inconsistencies among various reliability measures (90^{th} or 95^{th} percentile travel time, standard deviation, coefficient of variation, percent of variation, BT, BTI, TTI, skew statistic, misery index, frequency of congestion, and on-time arrival). The study explored the mathematical relationships and interdependencies of these measures. It was suggested that the coefficient of variation (instead of standard deviation) would serve as a good proxy for several other reliability measures.

Rakha et al. (2011) examined existing studies that had used video cameras and other onboard devices to collect data. They determined the potential for using such data to explore how to modify driver behavior to reduce non-recurring congestion and, hence, the travel time unreliability.

For selecting an appropriate measure, it is necessary to understand the characteristics and formulation of the measure. The comparative study by Wakabayashi and Matsumoto (2012) suggested that the combination of average travel time and appropriate travel time reliability index is important for assessing reliability of the route for both motorists and operators.

Williams et al. (2013) hypothesized that the reliability measures should not be strongly correlated with the average travel time to provide significant additional information. They found that all the well-established measures are correlated with the average travel time. Their study suggested skew statistic and semi-standard deviation as reliability measures, primarily because they are less correlated with average travel time. Moreover, these measures can identify location where non-recurring congestion is the primary source of congestion. These measures are also capable of providing a sense of the relative magnitude of non-recurring congestion.

Cambridge Systematics (2013) analyzed the effect of non-recurring congestion due to incidents, weather, work zones, special events, traffic control devices, demand, and bottlenecks. Their study explained the importance of travel time distributions for measuring reliability and recommended specific reliability performance measures. Numerous non-recurring congestion mitigation procedures were identified and models to predict such events were developed with an indication of their relative importance. The models were based on three empirical methods: before and after studies, a “data poor” approach that resulted in a parsimonious and easy-to-apply set of models, and a “data rich model” that used cross-section inputs including data on selected factors known to directly affect non-recurring congestion. It was found that travel time reliability can be improved by reducing demand, increasing capacity, and enhancing operations.

A summary of reliability measures proposed and used in the past is presented in Table 1.

Table 1: Reliability Measures - Summary

Index	Measure / Equation	Index	Measure / Equation
NCHRP (1998) Definition	Standard deviation of travel time	λ_{Skew} (van Lint et al., 2004)	$(TT_{90} - TT_{50})/(TT_{50} - TT_{10})$
AASHTO (2008) Definition	On-time performance	λ_{Var} (Bogers et al., 2008)	$(TT_{90} - TT_{10})/TT_{50}$
TranSystems Definition (2005)	Probability of on-time performance	Variability (Wakabayashi, 2010)	TT_{85}-TT_{15}
Buffer Time (BT) (Lomax et al., 2004)	$TT_{95} - TT_{Ave}$	Variability (Wakabayashi, 2010)	TT_{80}-TT_{20}
Buffer Time Index (BTI) (Lomax et al., 2004)	$\frac{TT_{95} - TT_{Avg}}{TT_{Avg}} \times 100$	Variability (Wakabayashi, 2010)	TT_{70}-TT_{30}
First worst travel time over a month (Wakabayashi & Matsumoto, 2012)	TT_{95}	Acceptable Travel Time Variation Index (Wakabayashi, 2010)	$P(TTavg + ATTV)$
Second worst travel time over a month (Wakabayashi & Matsumoto, 2012)	TT_{90}	Desired Travel Time Reduction Index (Wakabayashi, 2010)	$P(TTavg - DTTR)$
Planning Time (PT) (Wakabayashi & Matsumoto, 2012)	TT_{95}	Travel Time Index (TTI) (Lyman et al., 2008)	$\frac{TT_{Ave}}{TT_{free\ flow}}$
Planning Time Index (PTI) (Sisiopiku & Islam, 2012)	$\frac{TT_{95}}{TT_{free\ flow}}$	Frequency of Congestion (Lyman et al., 2008)	Percent of days/periods that are congested
Travel Time Variability (TTV) (Tu et al., 2007)	$TT_{90} - TT_{10}$		

2.3. Value of Travel Time

The value of time refers to the monetary value travelers place on reducing their travel time. There exists a vast body of literature on the theoretical underpinning of the value of travel time, and to a lesser extent on the value of reliability. In this report, the dollar value from past studies was converted into year 2014 Dollar value using the tool developed by Williamson (2008).

Preliminary studies on monetizing the travel delay include work by Moses and Williamson (1963) on motorists' value of time. They used a value of $1.55 per hour (estimated present value is $12.03 per hour), which is a little over the minimum wage (at the time of their publication). Beesley (1965) introduced the concept of traders (those willing to sacrifice cash for time or vice versa) with values of 30-43% of income given for traders. Their study concluded that there are yet insufficient grounds to reject earlier notions about the value of time. Lisco (1968) stated that the estimated traditional value is $0.86 per hour (estimated present value is $5.87 per hour), but recommended it to be increased to $2.82 per hour (estimated present value is $19.24 per hour).

Reichman (1973) estimated the motorists' implied value of time by asking, those already on a journey by various modes, questions such as how long they estimated the same trip would have taken by alternate modes. Each passenger was requested to separately report time differences by mode and time savings. It was observed that 21% of air passengers stated that their time savings amounted to quantities nearly twice as much as the mean of the difference in reported travel times. Sixteen percent of all bus passengers indicated the discrepancy between differences in time spent and time saved when asked how much time they would have saved traveling by air.

Gronau (1974) analyzed the previous studies and then developed a new method to estimate the value of motorists' time. It was pointed that the earlier approaches, which estimated the price of time using conventional methods of analysis (e.g., discriminate analysis, probit, and logit), may be appropriate for the analysis of modal split but are completely inadequate for the estimation of the value of time.

Keller (1975) tabulated the methods and results for nineteen studies before 1974. Guttman (1975) examined the measurement errors in the previous estimates of the value of time and presented a new set of estimates avoiding the errors. Guttman found that failure to consider motorists' uncertainty in making choice between alternate routes would bias the estimate by 50% or above. Also, the inability to account for cross-time substitutions by motorists in peak-hour conditions would result in errors. Peak-hour work trip time was estimated to have a value of $5.17

per hour (estimated present value is $22.82 per hour). While off-peak work trips were estimated to have a value of $1.91 (estimated present value is $8.43), off-peak social and recreational trips were estimated to have a value of $2.08 (estimated present value is $9.18).

Cesario (1976) found that benefit estimates obtained by explicitly considering travel time sustainability exceed estimates made when travel time is ignored. Cesario's estimates are substantially lower than the one by Cesario and Knetsch (1970), suggesting that the latter estimates are too high. The reason for the discrepancy is because of the trade-off functions in money and time implicitly considered. Cesario concluded that incorporating travel time valuations in recreation benefit analysis seems vastly superior to excluding them on both theoretical and practical grounds.

Wilman (1980) examined the role of time costs - both on-site and travel - in models describing recreational behavior, and found that both recreation and travel time are costly. The later can be valued in terms of its scarcity value, but the former may be most appropriately valued in terms of the "value of travel time saved." Suggestions as to how to measure the on-site and travel time costs were made by Wilman in his study.

Cherlow (1981) discussed several aspects of obtaining accurate valuations of travel time savings, particularly on commuting trips, emphasizing both the advantages and disadvantages of the various approaches used. Also, the factors that influence the valuation of travel time savings were identified and discussed in their research.

Hauer and Greenough (1982) employed a method to estimate the implied value of time. The experiment was conducted in the Toronto subway system, where they offered bribes to the people waiting for trains to miss their train and travel by a later train. They calibrated the implied value of time considering the delay demanded and by varying the amount offered. The variables they used were travel time (morning peak, mid-day, and afternoon peak), gender, and income level. The implied median value of an hour was $55 (estimated present value is $135.32) during the morning peak period for those who were just on time or late for their trip and $59 (estimated present value is $145.17) during the evening peak period. For those who were early and those who had no fixed arrival time, the values were $30 (estimated present value is $73.81) and $17 (estimated present value is $41.83), respectively.

The methods adopted to estimate the value of travel time varied from one researcher to another researcher. Haight (1994) identified the problems in estimating the comparative costs of safety and mobility, based on human capital and willingness to pay approaches, to see different results.

Litman (1999) researched on total North American road transportation costs, including non-market environmental and social costs and found that automobile use is significantly underpriced resulting in over-consumption and inefficient use of resources. The study also discussed the implications on sustainability criteria such as economic efficiency, equity, environmental impacts, and land use patterns. The study recommended the planners to incorporate total cost analysis in transport planning and policy analysis for better decision making. Existing estimates for a list of twenty costs defined for eleven modes and three travel conditions were summarized in their report, to provide average estimated costs per unit of passenger travel in North America.

In the 2008 Urban Mobility Report (2008), the total congestion cost for passenger cars and trucks were evaluated separately based on cost incurred per mile for each mode of transport. The cost per mile for each mode was calculated based on factors such as inflation, consumer price index (for trucks), fuel cost, operational cost, and average mileage. The evaluated costs were then multiplied with average speeds to evaluate cost per hour for each mode. Finally, the cost per hour was multiplied with associated delays to evaluate the cost of congestion for each mode of transport.

Kittelson and Vandehey (2013) presented four different options for defining reliability LOS. They are: (1) reliability LOS based on current LOS ranges, (2) freeway reliability LOS based on travel speed ranges, (3) freeway reliability LOS based on most restrictive condition, and, (4) reliability LOS based on the value of travel. However, no specific method was proposed or discussed to quantify the value of reliability.

As stated previously, there is a vast amount of literature on the value of travel time. A summary of data used and estimated value of time from selected studies is presented in Table 2.

Table 2. Value of Travel Time Proposed by Past Researchers

Study	Data Used	Value of Time Estimate
Becker (1965)		40% of wage rate
Beesley (1974)	Data from the survey of government employees in London, UK	31-50% of wage rate
Lisco (1968)		20-51% of wage rate
Miller (1989)	Survey of multiple route choice models	60% of gross wage
Small (1992)	Values derived from multiple mode choice transportation models	20 to 100% of gross wage; 50% is a reasonable average
Waters (1992)	Travel data from British Columbia, Canada	50-100% average wage rate for personal travel, depending on LOS; 120-170% of average wage rate for commercial travel, depending on LOS
Calfee and Winston (1998)	Data from National Family Opinion survey, covering commuters from major United States cities	14-26% of gross wage; 19% of wage - average estimate
Waters (1996)	Travel data from 15 studies in North America	40-50% of after tax wage rate
Small and Yan (2001)	Data on commute travelers on SR-91 in California	Average value of time is $22.87/hour (estimated present value is $30.68/hour); 72% of sample wage rate
Lomax et al. (2003)	Estimates are based on multiple sources of data	50-120% of the wage rate depending on type of travel
Brownstone and small (2005)	Travel data from electronic toll facilities in high occupancy toll (HOT) lanes on SR-91 and I-15 in Southern California	Value of time saved on the morning commute - $20-40/hour (estimated present value is $24.31-48.63/hour); 50% of average wage rate in the sample
Small, Winston and Yan (2005)	Travel from SR-91 in greater Los Angeles area (CA); Collected in June 2004	Median value of time is $21.46/hour (estimated present value is $26.09/hour) or 93% of average wage rate
Tseng et al. (2005)	Data for Dutch commuters who drive to work two or more times per week; Collected in June 2004	Mean value of time for all travelers
Litman (2007)	Results are drawn from multiple travel time studies	25-50% of prevailing wage for personal travel
Tialhun and Levinson (2007)	Data from stated preference survey of travelers on I-394, in Minneapolis/St. Paul area	$10.62/hour (estimated present value is $12.16/hour) for MN Pass subscribers that were early/ on-time; $25.42/hour (estimated present value is $29.11/hour) for MN Pass subscribers that were late; $13.63/hour (estimated present value is $15.61/hour) for non-subscribers that were early/on-time; $10.10/hour (estimated present value is $11.57/hour) for non-subscribers that were late.

2.4. Value of Reliability

The value of reliability relates to the monetary value travelers place on reducing travel time variations. Most travelers are aware of variability in their travel times, and so, they incorporate buffers to assure for on-time arrival. This implies that arriving late is “costly” and should be avoided (Cambridge Systematics, Inc. et al., 2013).

Abdel-Aty et al. (1997) collected data from two stated preference (SP) surveys and carried out a statistical analysis of commuter’s route choice. In the first survey, the user was asked to choose between two routes with distinct travel times (one with the same travel time on all days and the other with different travel times in a week). In the second survey, a section with traffic information was included to the previous survey. Binary logit models were used to analyze the survey data including variables such as standard deviation, mean and gender. They found that commuters consider reliability characteristics in their route preference (RP) and paid attention to travel information enough to be influenced in some scenarios to deviate from their usual routes. Another finding was that males tend to choose the uncertain route more than females, thus, indicating a difference in risk attitudes related to gender.

Lam and Small (2001) defined unreliability as the difference between 90th percentile travel time and median. They measured the value of time and reliability by observing the actual behavior of commuters on State Route 91 in Orange County, California. The driver has the option of choosing between a free and variable toll route. The estimated value of time is $22.87 per hour (estimated present value is $30.68 per hour), while the estimated value of reliability is $15.12 per hour (estimated present value is $20.28 per hour) for men and $31.91 per hour (estimated present value is $42.81 per hour) for women.

Nam et al. (2005) expressed reliability in terms of standard deviation and maximum delay that was measured based on triangular distribution. Multinomial and nested logit models were used for estimating the value of time and value of reliability. Results showed that reliability is an important factor affecting mode choice decisions.

Small et al. (2005) studied the distribution of commuter’s preferences for speedy and reliable highway travel. They stated that the value of travel time rarely accounts for reliability and tried to assess the distribution of values of travel time savings and reliability, allowing for both observed and unobserved heterogeneity. The final sample for their study consisted of RP data on 522 distinct individuals and SP data on 81 distinct individuals (55 of them also answered RP questions). In the SP survey, the respondent has the option of choosing between two identical routes with specified hypothetical tolls, travel times, and probabilities of delay. The lane choice depended on parameters; trip distance, annual per capita, age, gender, household income and size, and a dummy variable. They also explored other variables such as occupation, education, vehicle occupancy, and size of workplace. These variables had less influence and so were omitted from analysis. The estimated values of time and reliability from their study are shown in Table 3.

Table 3. Value of Time and Value of Reliability (Small et al., 2005)

Classification	RP Estimates
Value of time ($/hour)	21.46 (estimated present value is $26.09/hour)
Value of reliability ($/hour)	19.56 (estimated present value is $23.78/hour)

Small et al. (2005) defined variability as the upper tail of the distribution of travel times (difference between the 80th and 50th percentile travel times), arguing that this measure is better than a symmetric standard deviation, as motorists worry about being late than being early. Planning for the 80th percentile travel time would mean arriving late for only 20% of the trips. Accordingly, "travel time equivalents" are defined using both typical (average) and reliability components as the same unit. The travel time equivalent is mathematically represented as shown in Equation 3.

$$TT_e = TT_m + a * (TT_{80} - TT_{50}) \qquad \text{Eq. 3}$$

where,

TT_e = Travel time equivalent on the segment or facility,

a = Reliability Ratio (Value of Reliability / Value of Time),

TT_m = Mean travel time, and,

TT_{80} and TT_{50} are the 80th and 50th percentile travel times, respectively.

The equivalent delay value is then estimated by normalizing to segment length (delay per mile). The LOS ranges would then be set on delay per mile. Though this method provides a single composite value for facility performance, calculation methods and reliability ratios are required to be established. Strategic Highway Research Program (SHRP) 2 Project C04 suggests a range of 0.5 to 1.5, but a review of past studies suggests that the range is more in the 0.9-1.2 range (Kittelson

& Associates, 2012).

Liu et al. (2007) studied the variation of the value of time and the value of reliability with time. The estimated median of the value of time and the value of reliability were converted to current dollar rate (Table 4). The table depicts that the value of time had a peak during 7:00-7:30 AM, and the value of reliability had its low value during that time. The results indicate that, under the time-dependent formulation, travel-time savings may be more important than uncertain travel time when departure time is close to such time constraints as work-start time.

Table 4. Value of Time and Value of Reliability (Liu et al., 2007)

Time	5:00-5:30	5:30-6:00	6:00-6:30	6:30-7:00	7:00-7:30	7:30-8:00	8:00-8:30	8:30-9:00	9:00-9:30	9:30-10:00
Value of Time ($/hour)	18.89	21.22	25.22	26.30	31.67	28.24	27.75	26.54	22.4	7.81
Value of Reliability ($/hour)	44.93	29.38	27.03	26.68	23.50	27.04	24.05	25.80	20.0	25.97

Chang (2010) assessed travel time reliability based on variation in trip time that travelers may not predict. The study considered average trip time as planned travel time for measuring reliability. Road reliability models were developed for both urban and inter-regional roads. Further, roads were classified into interrupted and uninterrupted facilities. To estimate the value of travel time and travel time reliability, a SP survey (in which the user has the choice to select among different travel modes) was conducted. Each travel mode has certain set of attributes which define the system (in-vehicle time, out-of-vehicle time, travel costs, and unexpected additional delay). A preliminary survey was conducted to obtain the values of the attributes. Table 5 shows the estimated results of inter-regional working, inter-regional non-working, and urban trips.

Tilahun and Levinson (2010) conducted a SP survey to understand traveler’s route preference. They explored the trade-offs motorists make when choosing routes and tried to explore three distinct measures of reliability such as lateness probability, standard deviation, and time moment. In all cases, reliability was measured high. The value of time from model 1 was estimated as $7.44 per hour (estimated present value is $8.10 per hour), while the value of reliability was estimated as $7.11 per hour (estimated present value is $7.74 per hour). The value of time was estimated as $8.07 per hour (estimated present value is $8.79 per hour), while the value of reliability was estimated as $2.31 per hour (estimated present value is $2.52 per hour) - much lower than the reliability measured from model 2. The value of reliability for model 3 was estimated as $6.93 per hour (estimated present value is $7.55 per hour), while the value of time was estimated at $7.82 per hour (estimated present value is $8.51 per hour).

Table 5. Value of Time and Value of Reliability (Chang, 2010)

Classification	Inter-regional		Urban
	Working	Non-Working	
Value of time (Won/hour) (2014 US $/hour)	10,435 (10.12)	3,320 (3.21)	8,878 (8.60)
Value of reliability (Won/hour) (2014 US $/hour)	8,087 (7.84)	2,714 (2.62)	8,328 (8.07)
Value of reliability / Value of time	0.77	0.82	0.94

He (2012) estimated the value of travel time and the value of reliability using I-394 dynamic toll data. Mixed logit model was used to calculate the probability of a traveler choosing high occupancy toll (HOT) lane. The estimated value of time ranged from $5.05 to $9.79 per hour (estimated present value is $5.22-10.12 per hour) with an average of $7.67 per hour (estimated present value is $7.93 per hour). The estimated value of reliability ranged from $6.36 to $13.41 per hour (estimated present value is $6.58-13.87 per hour) with an average of $9.94 per hour (estimated present value is $10.28 per hour). They concluded that high reliability ratios indicate that motorists are willing to pay more for travel time reliability than for travel time. The value of time and the value of reliability on Friday are higher than other days.

Carrion and Levinson (2012) conducted a systematic review of travel time reliability, more explicitly on the value of travel time reliability. They examined various studies that were conducted to estimate the value of travel time reliability. Consequently, they stated that the value of reliability exhibits significant variation across studies. This may be due to differences in experimental design, theoretical framework, and variability measures, setting the preferred arrival time, data source, or other. They conducted an analysis to determine the reasons behind the discrepancy among the reliability estimates.

2.5 Limitations of Past Research

Overall, literature documents limited and inconclusive research on the value of reliability. Additionally, most of the past studies estimated the value of reliability using discrete choice models. Moreover, a clear definition of reliability was not stated before estimating the value of reliability.

The definition of reliability could influence the value of reliability and data required to assess the impact of transportation alternatives. The effect of trip length (travel time) and the number of days per month a route is unreliable are other factors that could have bearing on the value of reliability. This research project documents efforts to overcome the aforementioned shortcomings and estimate the value of reliability for the state of North Carolina.

Chapter 3. Assessment of Travel Time Reliability Measures

This chapter presents an assessment of selected travel time reliability measures, using correlation analysis, to recommend suitable measures for use by NCDOT. It is primarily based on research and outcomes from a project conducted for the United States Department of Transportation (Pulugurtha et al., 2015; Pulugurtha et al., 2016).

3.1. Data Collection

Raw data for the city of Charlotte, North Carolina for each TMC or link in the transportation network was obtained from INRIX (INRIX, 2014). The raw data file has Traffic Message Channel (TMC) code (tmc_code), time-stamp (measurement_tstamp), speed (speed), average speed (average_speed), reference speed (reference_speed), travel time (travel_time_minutes) and score (confidence_score). Each field in the raw data file is briefly described next (INRIX, 2013).

1. Traffic Message Channel (TMC) - defines identity of the road segment.
2. Speed - current estimated space mean speed for the road segment in miles per hour.
3. Average speed - historical average mean speed for the road segment in miles per hour, for that time-of-the-day (hour) and day-of-the-week.
4. Reference speed - calculated "free flow" mean speed for the road segment in miles per hour. It is the 85th percentile point of the observed speeds on that segment.
5. Travel time - current estimated time it takes to traverse the road segment in minutes.
6. Score - an indicator of data type (30 indicates real-time data; 20 indicates real-time data across multiple segments; 10 indicates historical data).

3.2. Selection of Performance Measures

Table 1 summarizes different travel time reliability measures that were defined and used by practitioners and researchers in the past. Out of them, six reliability indices or variance related measures were considered in this study. They are briefly described next.

1. Buffer time (BT): It is the difference of the 95th percentile travel time and the average travel time. It represents the required additional time for an on-time performance (Lomax et al., 2004).

$$\text{Buffer time (BT)} = TT_{95} - TT_{Avg} \qquad \text{Eq. 4}$$

2. Buffer time index (BTI): It is the ratio of the difference of the 95th percentile travel time and the average travel time to the average travel time (Lyman and Bertini, 2008; Lomax et al., 2004).

$$\text{Buffer time index (BTI)} = \frac{TT_{95} - TT_{Avg}}{TT_{Avg}} \times 100 \qquad \text{Eq. 5}$$

3. Planning time index (PTI): It is the ratio of the 95th percentile travel time and the free flow travel time or the 15th percentile time (Lyman and Bertini, 2008; Sisiopiku and Islam, 2012).

$$\text{Planning time index (PTI)} = \frac{TT_{95}}{TT_{free\ flow}} \qquad \text{Eq. 6}$$

4. Travel time index (TTI): It is the ratio of the average travel time to the free flow travel time (Lyman and Bertini, 2008).

$$\text{Travel time index (TTI)} = \frac{TT_{Avg}}{TT_{free\ flow}} \qquad \text{Eq. 7}$$

5. λ skew: It is the ratio of the difference in the 90th percentile and the 50th percentile travel times to the difference in the 50th percentile and the 10th percentile travel times (van Lint et al., 2004).

$$\lambda \text{ skew} = (TT_{90} - TT_{50})/(TT_{50} - TT_{10}) \qquad \text{Eq. 8}$$

6. λ variance: It is the ratio of the difference between 90th percentile and 10th percentile to the 50th percentile travel time (Bogers et al., 2006).

λ variance = $(TT_{90} - TT_{10})/TT_{50}$ Eq. 9

The following travel time, travel time percentile, and travel time variation related performance measures were also considered in addition to the aforementioned travel time reliability indices or variance related measures.

- Minimum travel time (Min TT), average travel time (Avg TT) and maximum travel time (Max TT)
- 10th, 15th, 50th, 85th, 90th, and 95th percentile travel times
- Travel time variation based on 85th, 90th, and 95th percentile travel times, which are computed as (TT85 - TT15), (TT90 - TT10) and (TT95 - TT5), respectively

3.3. Data Processing & Computation of Reliability Measures

The data processing was performed using Microsoft SQL server. Data tools and query applications were developed to compute the various performance measures. The factors considered in computing these travel time based measures are time-of-the-day and day-of-the-week. The statistical analysis was carried out for various day-of-the-week categories: Monday, Wednesday, Friday, Saturday, Weekday (Monday to Friday), Weekend (Saturday and Sunday) and all days. For each day-of-the-week considered, data was extracted and analyzed for morning peak hour (8 AM - 9 AM), daytime off-peak hour (12 PM -1 PM), evening peak hour (5 PM - 6 PM), nighttime off-peak hour (9 PM - 10 PM) and all day.

A total of 35 datasets, for each year, were prepared for the analysis. The sample size of each dataset varied with the time-of-the-day and year (depends on data gathered and available for analysis). The Pearson correlation coefficient matrices were then developed to examine the inter-relationships between the selected travel time based measures for each year (2009 to 2012).

SPSS statistical analysis software (IBM SPSS20, 2011) was used for developing the Pearson correlation coefficient matrices. Readers are encouraged to refer to Pulugurtha et al. (2015) for the correlation matrices for all selected time periods and days of the weeks, for years 2009, 2010, 2011 and 2012, or other project related findings.

The following criteria were used to assess the relationship based on computed Pearson correlation coefficients. The medium and high correlations are at least at a 95% or higher confidence level.

Low Correlation ~ (-0.3 to 0.3)
Medium Correlation ~ (-0.7 to -0.3 or 0.3 to 0.7)
High Correlation ~ (-1.0 to -0.7 or 0.7 to 1.0)

3.4. Relationship between Travel Time Data Based Measures

Among all the travel times, the minimum travel time, maximum travel time, and average travel time are mainly considered for the analysis. From the reliability measures, the BT, BTI, PTI and the TTI are considered for the analysis. Tables 6 and 7 summarize the inter-relationships between these selected travel time data based measures. In each of the tables, the relationship between the selected measures with all other measures is observed for the selected time-of-the-day and day-of-the-week. The letter "H" indicates that it is highly correlated, the letter "M" indicates that it is moderately correlated, and the blank field indicates that the two measures are not correlated (low).

The summary results from Table 6 indicate that the reliability measures (except the BT) are moderately correlated with the minimum travel time. The buffer time is highly correlated with the minimum travel time for almost all the selected time periods. The summary results from Table 6 also show that the maximum travel time is highly correlated with all the travel time measures. The travel time variations and the buffer time are also highly correlated with the maximum travel time, with exceptions in some cases. The reliability measures are moderately correlated with the maximum travel time. However, reliability measures are highly correlated with the maximum travel time in the case of weekday (8 AM - 9 AM) and weekday (5 PM - 6 PM). The average travel time has a good correlation with all the travel times, travel time variations and buffer time (also shown in Table 6). However, it is not correlated with the BTI, PTI, λ skew, λ variance and TTI.

Table 7 summarizes the correlation between buffer time with other travel time and reliability measures. The results show a good correlation with all the travel time and reliability measures. It only shows some variation in its correlation with the λ skew. Table 7 also indicates that the travel time measures are not correlated with the BTI. However, in the case of travel time variability indices and reliability measures, there is a good correlation with the BTI. The PTI also shows similar trends as the BTI (Table 7). It is not correlated to the travel time measures but correlated with the travel time variability and reliability measures. A variation in correlation between PTI and λ skew is observed. Likewise, the TTI does not have a correlation with travel time measures. Among the reliability measures, except the λ skew, all the values are correlated with TTI.

The travel time measures (minimum, average and maximum) indicate the performance of a link or a corridor. The minimum travel time indicates the free flow condition for the selected time-of-the-day and day-of-the-week, while the maximum travel time accounts for the effect of non-recurring events (worst case scenario) on the link or corridor performance. The average travel time accounts for the centrality between these two states. It is an indicator of the expected travel time.

The travel time, travel time variations and travel time percentiles (10th percentile to the 95th percentile travel times) are applicable for before and after evaluations. They can help assess the performance of a link or corridor but cannot be used to compare the performance of a link or corridor with another link or corridor. This is because the length, traffic speed or speed limit, traffic volume and road characteristics vary from one link or corridor to another link or corridor in the transportation network.

The average travel time is correlated to all the travel time, travel time percentile and travel time variation based measures. It is therefore recommended for use in assessing the performance of a link or corridor as well as for before and after evaluations (say, if the average travel time has decreased after implementing a project).

Performance measures such as BT and PT are incomparable between different links or corridors. However, buffer time is the only measure that is correlated with almost every other travel time data based measure considered in this study. It assists transportation system users plan their trips to reach their destination on time (in particular, when unreliable).

The other travel time reliability and variance measures (BTI, PTI, λ skew, λ variance, and TTI) can be used to evaluate the condition of a facility (level of congestion or reliability). They can also be used to compare performance of a link or corridor with another link or corridor (ranking and prioritization for allocation of resources). The BTI is found to be correlated to all other travel time reliability indices and variance based measures and, therefore, recommended for use in ranking and prioritization for allocation of resources.

Table 6. Summary of Results Showing Correlation with Travel Time Measures

Day-of-the-week & Time-of-the-day	Min. TT	Max. TT	Avg. TT	10th Percentile TT	15th Percentile TT	50th Percentile TT	85th Percentile TT	90th Percentile TT	95th Percentile TT	TTV - 90	TTV - 85	TTV - 95	BT	BTI	PTI	λ Skew	λ Var	TTI
Correlation of with the Minimum Travel Time																		
Wednesday All Day	H	H	H	H	H	H	H	H	H	H	H	H	H				M	
Saturday All Day	H	H	H	H	H	H	H	H	M	M	M	M						
Weekday All Day	H	H	H	H	H	H	H	H	H	H	M	H	M					
Weekend All Day	H	H	H	H	H	H	H	H	M	M	M	M						
Weekday (8 AM-9 AM)	H	H	H	H	H	H	H	H	H	M	M	M	M					
Weekday (12 PM-1 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M	M	M	M	
Weekday (5 PM-6 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M				
Weekday (9 PM-10 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M	M	M	M	
Weekend (8 AM-9 AM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M	M	M	M	
Weekend (12 PM-1 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M	M	M	M	
Weekend (5 PM-6 PM)	H	H	H	H	H	H	H	H	H	H	H	M	M					
Weekend (9 PM-10 PM)	H	H	H	H	H	H	H	H	H	H	M	H	H	M	M		M	
Correlation with the Maximum Travel Time																		
Wednesday All Day	H	H	H	H	H	H	H	H	H	H	H	H	H	M	M			
Saturday All Day	H	H	H	H	H	H	H	H	H	H	H	H	M		M	M		M
Weekday All Day	H	H	H	H	H	H	H	H	H	H	M	H	H					
Weekend All Day	H	H	H	H	H	H	H	H	H	H	H	H	M		M	M		M
Weekday (8 AM-9 AM)	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	M	H	H
Weekday (12 PM-1 PM)	H	H	H	H	H	H	H	H	H	H	M	H	M	M			M	
Weekday (5 PM-6 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	M	H	H
Weekday (9 PM-10 PM)	H	H	H	H	H	H	H	H	H	M	M	M	M	M				
Weekend (8 AM-9 AM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M				
Weekend (12 PM-1 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H				M	
Weekend (5 PM-6 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M	M	M	M	M
Weekend (9 PM-10 PM)	H	H	H	H	H	H	H	H	H			M	M	M				
Correlation with the Average Travel Time																		
Wednesday All Day	H	H	H	H	H	H	H	H	H	H	H	H	H					
Saturday All Day	H	H	H	H	H	H	H	H	H	H	H	H	M	M	M	M		M
Weekday All Day	H	H	H	H	H	H	H	H	H	H	H	H	H					
Weekend All Day	H	H	H	H	H	H	H	H	H	M	H	H	M	M	M	M		M
Weekday (8 AM-9 AM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M	H		M	M
Weekday (12 PM-1 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M		M	M	
Weekday (5 PM-6 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M	M		M	M
Weekday (9 PM-10 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M		M	M	
Weekend (8 AM-9 AM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M		M	M	
Weekend (12 PM-1 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	M		M	M	
Weekend (5 PM-6 PM)	H	H	H	H	H	H	H	H	H	H	H	H	M					
Weekend (9 PM-10 PM)	H	H	H	H	H	H	M	H	H	H	H	H	H	M			M	

Table 7. Summary of Results Showing Correlation with Reliability Measures

Day-of-the-week & Time-of-the-day	Min. TT	Max. TT	Avg. TT	10th Percentile TT	15th Percentile TT	50th Percentile TT	85th Percentile TT	90th Percentile TT	95th Percentile TT	TTV - 90	TTV - 85	TTV - 95	BT	BTI	PTI	λ Skew	λ Var	TTI
Correlation with the BT																		
Wednesday All Day	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	M
Saturday All Day		M	M	M	M	M	M		H	H	H	H	H	H	H	H	H	M
Weekday All Day	M	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	M
Weekend All Day		M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	H	
Weekday (8 AM-9 AM)	M	H	H	M	M	H	H	H	H	H	H	H	H	H	H	H	H	H
Weekday (12 PM-1 PM)	H	M	H	H	H	H	H	H	H	H	H	H	H	H	H		H	H
Weekday (5 PM-6 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
Weekday (9 PM-10 PM)	H	M	H	H	H	H	H	H	H	H	H	H	H	H	H	M	H	H
Weekend (8 AM-9 AM)	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H		H	H
Weekend (12 PM-1 PM)	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H		H	H
Weekend (5 PM-6 PM)	M	H	M	M	M	M	M	H	H	H	H	H	H	H	H	H	H	H
Weekend (9 PM-10 PM)		M	H	H	H	H	H	H	H	H	H	H	H	H	H		H	H
Correlation with the BTI																		
Wednesday All Day		M							H	H	H	H	H	H	H	H	H	H
Saturday All Day			M	M					H	H	H	H	H	H	M	H	H	
Weekday All Day								M	H	H	M	H	H	H	H	H	H	H
Weekend All Day			M	M					H	H	H	H	H	H		H	H	
Weekday (8 AM-9 AM)		H	M			M	H	H	H	H	H	H	H	H	H	H	H	H
Weekday (12 PM-1 PM)	M	M	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	H
Weekday (5 PM-6 PM)	M	H	M				M	H	H	H	H	H	H	H	H	H	H	H
Weekday (9 PM-10 PM)	M	M	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	H
Weekend (8 AM-9 AM)	M	M	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	H
Weekend (12 PM-1 PM)	M		M	M	M	M	M	M		H	H	H	H	H	H	H	H	H
Weekend (5 PM-6 PM)		M						M	H	H	H	H	H	H	H	H	H	H
Weekend (9 PM-10 PM)	M	M	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	H
Correlation with the PTI																		
Wednesday All Day		M						M	M	H	H	H	H	H	H	H	H	H
Saturday All Day		M	M	M	M	M	M	M					H	M	H	M		
Weekday All Day								M	M	H	H	H	H	H	H	H	H	H
Weekend All Day		M	M	M	M	M	M	M					H		H	M		
Weekday (8 AM-9 AM)		H	H			M	H	H	H	H	H	H	H	H	H	H	H	H
Weekday (12 PM-1 PM)	M			M	M					H	H	H	H	H	H		H	H
Weekday (5 PM-6 PM)		H	M			M	H	H	H	H	H	H	H	H	H	H	H	H
Weekday (9 PM-10 PM)	M			M	M					H	H	H	H	H	H	M	H	H
Weekend (8 AM-9 AM)	M			M	M					H	H	H	H	H	H		H	H
Weekend (12 PM-1 PM)	M			M	M					H	H	H	H	H	H		H	H
Weekend (5 PM-6 PM)		M						M	H	H	H	H	H	H	H	H	H	H
Weekend (9 PM-10 PM)	M			M	M					H	H	H	H	H	H		H	H
Correlation with the TTI																		
Wednesday All Day									M	H	H	H	M	H	H	M	H	H
Saturday All Day		M	M	M	M	M	M	M	M	M	M		M					H
Weekday All Day									M	H	H	H	M	H	H	M	H	H
Weekend All Day		M	M	M	M	M	M	M	M	M	M							H
Weekday (8 AM-9 AM)		H	M			M	H	H	H	H	H	H	H	H	H	M	H	H
Weekday (12 PM-1 PM)				M	M					H	H	H	H	H	H		H	H
Weekday (5 PM-6 PM)		H	M			M	H	H	H	H	H	H	H	H	H	H	H	H
Weekday (9 PM-10 PM)				M						H	H	H	H	H	H		H	H
Weekend (8 AM-9 AM)										H	H	H	H	H	H		H	H
Weekend (12 PM-1 PM)										H	H	H	H	H	H		H	H
Weekend (5 PM-6 PM)		M						M	M	H	H	H	H	H	H		H	H
Weekend (9 PM-10 PM)					M					H	H	H	H	H	H		H	H

Chapter 4. Methodology

This chapter describes the sampling strategy, survey plan, and survey questionnaire design.

4.1. Sampling Strategy

The sample size dictates how well the sample reflects the population. The higher the sample size, the more reliably it reflects the population mean. Equations 10 and 11 are used to compute the sample size.

$$ss = \frac{p*(1-p)*Z^2}{c^2} \quad \text{Eq. 10}$$

$$N = \frac{ss}{1+\frac{ss-1}{pop}} \quad \text{Eq. 11}$$

where,

Z = Z value (example, 1.96 for 95% confidence level),

p = percentage picking a choice, expressed as decimal (0.5),

c = confidence interval, expressed as decimal (0.05),

ss = sample size,

N = final sample size, and,

pop = population.

The population of the state of North Carolina from 2013 census data is 9,848,060. The sample size obtained by substituting this value in equations 10 and 11 is 384. Any sample size greater than 384 participants increases the reliability of the results obtained from the research.

Survey participants are generally selected randomly. Selecting participants randomly could also lead to biased results, if most of the randomly selected participants are from a particular group. To eliminate this bias, a stratified sampling method is adopted. In this method, the entire sampling framework is divided into groups of interest (example, age, gender, income group, and region or area). A simple random sampling or systematic random sampling is adopted within each group. Past researchers differentiated the value of reliability between male and female. Besides gender, the value of reliability may vary by income and other demographic characteristics. Therefore, the surveys also aimed at collecting different demographic characteristics of the participants.

The proposed plan is to collect the same percentage of male and females as in the census data (Table 8). Females contribute to 51.3% of the total population in the state of North Carolina. It is important to ensure and collect the same percentage of female participants for unbiased results. Table 8 also shows the minimum number of samples required by gender for the survey.

Table 8. Samples Required by Gender

Gender	Samples Required	% of North Carolina Population
Male	187	48.7
Female	197	51.3
Total	384	100.0

As stated previously, the value of reliability varies with the income of an individual, flexibility of job timings, type of the trip and location (city, town or other area) of the individual. To estimate the overall value of reliability for the state of North Carolina, participants from different income groups should be involved in the survey. Table 9 shows the percentage of population by income group and sample size planned for collection by income group.

Table 9. Samples Required by Income Group

Income Groups	Samples Required	% of North Carolina Population
< $15,000	56	14.6
$15,000 - $25,000	46	12.1
$25,000 - $35,000	45	11.8
$35,000 - $50,000	57	14.8
$50,000 - $75,000	70	18.1
$75,000 - $100,000	43	11.3
$100,000 - $150,000	40	10.5
$150,000 - $200,000	14	3.5
> $200,000	13	3.3
Total	384	100.0

The value of reliability varies with the region or city, town or other area in which the person resides. A person living in a city may value reliability differently from a person living in a town or village. For this study, municipalities with population greater than 50,000 were considered as cities, and those with population less than or equal to 49,999 are considered as towns. Table 10 summarizes the percentage of population living in cities, and, towns and other (includes all other municipality types except cities) in the state of North Carolina.

Table 10. Percentage of Population Living in Cities, Towns, and Villages

Description	Samples Required	% of North Carolina Population
Cities	211	55.0
Towns and Other	173	45.0
Total	384	100.0

The proposed sampling process aimed to collect data from four cities: Charlotte, Raleigh, Ashville, and Greensboro. The towns selected for conducting survey are Apex, Huntersville and other random locations in North Carolina. Locations were identified to conduct the survey in each selected city, town and village. These locations include gas-stations, shopping malls, warehouses or small commercial centers. Overall, the survey needs to be conducted such that it meets minimum sample requirements based on the aforementioned characteristics.

4.2. Survey Plan

The data from participants to monetize reliability through survey is collected in three stages, a preliminary random general survey followed by focus group survey and final random survey. The preliminary random general survey was conducted from February 2015 through May 2015, while the focus group survey was carried out from July 2015 through November 2015. The final random survey was conducted from February 2016 through March 2016.

Data was preliminarily collected, randomly, from 417 participants at seven different cities, towns and other areas. The locations at which data was collected included gas stations, grocery stores, shopping malls and major employment centers in case of preliminary random general survey. At each location, a group of five trained students collected survey data from random people, for at least one hour to meet the minimum number of samples for each location.

In case of focus group survey, the preliminary random general survey questionnaire was revised after thorough discussions with NCDOT Technical Advisory Committee. Before carrying out the focus group survey, potential participants were asked whether they have already participated in the preliminary random general survey. None of the focus group participants participated in the preliminary random general survey.

The focus group survey aimed to collect at least 50 samples by engaging participants in discussions at eight focus group meetings. Overall, the research team has conducted nine focus group meetings with number of participants ranging from a minimum of 6 to a maximum of 21 people in these meetings. A total of 93 survey samples were obtained from the focus group meetings.

Like in the case of preliminary random general survey, the final random survey was conducted to collect data from 357 participants in four different cities, towns and other areas across North Carolina.

Only participants with valid driver's license that are in the age group of 20-75 years were allowed to participate in the surveys. All the participants taking the survey can understand and speak English language. Each randomly selected participant was asked to answer the survey questions if he/she met the above requirements and was interested in participating in the survey.

4.3. Survey Questionnaire

The preliminary random general survey questionnaire comprised of 12 questions. The questions were aimed to capture participant details (level of education and income) and acceptable tolerance levels for different types of trips (work, school, shopping, social and recreational; by time-of-the-day and day-of-the-week). A few questions in the survey are stated preference choices on evaluating how the participants would react to hypothetical situations. They were asked to choose among routes based on a description of the route provided as options. The preliminary random general survey questionnaire form used in this research is shown in Figure 1 and Figure 2.

As stated previously, the preliminary random general survey questionnaire was revised after thorough discussions with NCDOT Technical Advisory Committee to gauge focus group participant's perception on the lack of reliability and various tolerance factors (how long and number of days they can tolerate the lack of reliability during a month). The focus group survey questionnaire form used in this research is shown in Figure 3 and Figure 4. This questionnaire was also used in case of final random survey.

NCDOT Project ID RP2015-07

Monetizing Reliability to Evaluate the Impact of Transportation Alternatives

Survey Questionnaire

1. Gender:
   ☐ Male ☐ Female

2. Age group:
   ☐ 20-34 years ☐ 35-54 years ☐ 55-74 years

3. What is your highest education level (If currently enrolled, indicate highest degree received)?
   ☐ High school graduate, diploma or the equivalent (for example: GED)
   ☐ Bachelor's degree
   ☐ Master's degree
   ☐ Professional degree
   ☐ Doctorate degree
   ☐ None of the above

4. Employer type:
   ☐ For-profit company or business
   ☐ Non-profit, tax-exempt, or charitable organization
   ☐ Local government employee (city, county, etc.)
   ☐ State government employee
   ☐ Federal government employee
   ☐ Self-employed - own not-incorporated business, professional practice, or farm
   ☐ Self-employed - own incorporated business, professional practice, or farm
   ☐ Working without pay in family business or farm
   ☐ Other

5. Which city / town (or zip code) you live in: _________________

   Which city / town (or zip code) you work in:_________________

6. Gross individual income:
   ☐ Less than $14,999
   ☐ $15,000 to $24,999
   ☐ $25,000 to $34,999
   ☐ $35,000 to $49,999
   ☐ $50,000 to $74,999
   ☐ $75,000 to $99,999
   ☐ $100,000 to $149,999
   ☐ $150,000 to $200,000
   ☐ $200,000 or more

7. Vehicle you use daily _____________/____________/_______ (Example: Toyota/Camry/1998)

8. Assume that there are two routes available. Given the route descriptions below, which one do you prefer for your daily commute?

   ☐ Travel time for a one-way trip on all days is 25 minutes.
   ☐ Travel time varies from 15 minutes to 35 minutes.

9. How much time does it take to travel to your workplace on an average? ______ Minutes. If you have to reach your workplace by 8:00 a.m., at what time do you normally start? ___:___ a.m.

Figure 1. Preliminary Random General Survey Questionnaire Form Page-1

10. Accounting for traffic congestion and related uncertainty, apart from your average travel time how early would you leave for your work?

To meet your superior during rush hours. ______ minutes
To meet your superior during non-rush hours. ______ minutes
To meet your inferior during rush hours. ______ minutes
To meet your inferior during non-rush hours. ______ minutes

11. Would your planned additional time proportionally increase with travel distance?

☐ Yes ☐ No

12. Select your preferred option.

☐ I don't mind leaving early to reach the destination on time.
☐ I don't mind paying a toll to reach the destination on time so that I do not need to start early.

13. How much are you willing to pay as toll for a one-way trip to reduce your trip travel time by (**Circle the maximum amount you would be willing to pay)**

0 - 2 minutes	\$0.25	\$0.50	\$1.00	\$1.50	\$2.00	\$2.50
2 - 5 minutes	\$0.25	\$0.50	\$1.00	\$1.50	\$2.00	\$2.50
5 - 10 minutes	\$0.25	\$0.50	\$1.00	\$1.50	\$2.00	\$2.50

14. Would you plan for additional trip time in case of recreational, social or shopping trips during peak hours on weekdays?

☐ Yes ☐ No

during off-peak traffic hours or weekends?

☐ Yes ☐ No

Figure 2. Preliminary Random General Survey Questionnaire Form Page-2 (Cont.)

General Information

1) Gender:
    - Male
    - Female

2) Age group:
    - 20-34 years
    - 35-54 years
    - 55-74 years
    - 75 years or older

3) Education (highest degree or level of school you completed; If currently enrolled, indicate highest degree received):
    - High school graduate, diploma or the equivalent (for example: GED)
    - Bachelor's degree
    - Master's degree
    - Professional degree
    - Doctorate degree
    - None of the above

4) Employer type:
    - For-profit company or business
    - Not-for-profit, tax-exempt, or charitable organization
    - Local government employee (city, county, etc.)
    - State government employee
    - Federal government employee
    - Self-employed - own not-incorporated business, professional practice, or farm
    - Self-employed - own incorporated business, professional practice, or farm
    - Working without pay in family business or farm
    - Other

5) Gross individual income:
    - Less than $14,999
    - $15,000 to $24,999
    - $25,000 to $34,999
    - $35,000 to $49,999
    - $50,000 to $74,999
    - $75,000 to $99,999
    - $100,000 to $149,999
    - $150,000 to $200,000
    - $200,000 or more

Figure 3. Focus Group Survey Questionnaire Form Page-1

User's Perspective on Reliability

6) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days during a month (20 working days) is 25 min.
   b) Route 2: The travel time on most of the days is 20 min, whereas on 2 unexpected days out of 20 working days it is 35 min.

7) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days during a month (20 working days) is 25 min.
   b) Route 2: The travel time on most of the days is 20 min, whereas on 4 unexpected days out of 20 working days it is 35 min.

8) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days during a month (20 working days) is 25 min.
   b) Route 2: The travel time on most of the days is 20 min, whereas on 6 unexpected days out of 20 working days it is 35 min.

9) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days during a month (20 working days) is 25 min.
   b) Route 2: The travel time on most of the days is 20 min, whereas on 8 unexpected days out of 20 working days it is 35 min.

User's Route Choice

10) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days is 25 min.
   b) Route 2: The travel time is not consistent. It can range between 20 to 30 min.

11) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days is 25 min.
   b) Route 2: The travel time is not consistent. It can range between 20 to 40 min.

12) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days is 25 min.
   b) Route 2: The travel time is not consistent. It can range between 20 to 50 min.

13) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days is 25 min.
   b) Route 2: The travel time is not consistent. It can range between 20 to 60 min.

Reliability & Willingness to Pay

14) From the above questions (5 to 8), you might have chosen Route 1 instead of Route 2. For that scenario,
   a) Assuming an organization is willing to pay you to forego the reliable route (i.e., Route 1). What amount are you willing to accept to take the unreliable route (i.e., Route 2) by foregoing the reliable route? $________
   b) Similarly, if you are asked to pay when you take the reliable route, what maximum dollar amount are you willing to pay? $______

15) For the trips mentioned below, what kind of reliability are you expecting on a roadway?
   a) To work: ☐ Highly reliable ☐ Moderately reliable ☐ Unreliable
   b) To home: ☐ Highly reliable ☐ Moderately reliable ☐ Unreliable

16) If you feel the roadway you use daily is unreliable, would you be willing to pay to make it reliable?
   ☐ Yes ☐ No

Figure 4. Focus Group Survey Questionnaire Form Page-2

Chapter 5. Preliminary Random General Survey Results

This chapter presents the results from preliminary random general survey responses collected across North Carolina. A total of 417 samples were collected during weekdays and daylight hours. The locations for data collection were selected randomly such that they are geographically distributed across each city, town or other area. People who were using locations such as gas stations were asked if they are interested in participating in a short survey. Two female students were also involved in the data collection, to encourage participation of females in the survey. Two out of four approached males were eager to participate in the survey, whereas the response rate is comparatively low in case of females.

Some participants did not provide travel time information, while a few others reported three or more times higher additional trip time than the average travel time. Data gathered from such participants were considered as outliers and ignored from detailed analysis. The total sample size after removing outliers is 345. Table 11 summarizes the percent of samples collected by age group and gender, after removing outliers.

Table 11. Samples Collected by Age and Gender - Preliminary Random General Survey

Age Group	Gender		Grand Total
	Male	Female	
20-34	30.72%	22.90%	53.62%
35-55	26.96%	9.86%	36.82%
56-75	6.09%	2.90%	8.99%
Unknown*			0.57%*
Total	63.77%	35.66%	100.00%

* Indicates that both the age and gender were not mentioned

The city, town or other area where the participants reside or work may affect their perception on reliability. The plan is to collect 55% of the total samples from people who are residing in cities and the remaining samples from towns or other areas. Table 12 shows the number of samples collected from different cities, towns and other areas in the state of North Carolina.

Besides age and gender, a few other demographic characteristics such as participants' income and level of education were also collected through the preliminary random general survey. Income could play a major role on the perception of reliability and its value. Travelers with high income may be willing to spend more money for travel time savings or their value for reliable routes could be higher.

Table 13 shows the percent of samples collected by income group. The percentage of samples collected in each income group was almost the same as the expected percentage. People belonging to high income group (judged based on the make and model of the vehicle they drive) were not interested to participate in the survey when compared to low income group, though the surveyors managed to gather adequate number of samples. Income group $50,000-$75,000, however, had comparatively lower participation (number of samples). Except that income group, rest all income groups had very less difference between anticipated and collected percent of samples.

Table 12. Number of Samples Collected by City, Town or Other Area - Preliminary Random General Survey

City, Town or Other Area	Total Samples
Ashville	38
Charlotte and Surrounding Suburbs	116
Greensboro	41
Raleigh-Durham Triangle Area	44
Other	93
Unknown	13
Total	345

Table 13. Percent of Samples Collected by Income Group - Preliminary Random General Survey

Income Group	% of Samples
< $15,000	13.91
$15,000 - $25,000	11.01
$25,000 - $35,000	13.91
$35,000 - $50,000	15.36
$50,000 - $75,000	14.49
$75,000 - $100,000	10.43
$100,000 - $150,000	8.99
$150,000 - $200,000	2.61
> $200,000	4.64
Unknown	4.64
Total	100.00%

Overall, the average annual income of the 345 participants (after removing outliers) is ~$63,518. The average wage rate is ~$0.51 per minute ($30.54 per hour).

5.1. Average Travel Time and Preliminary Random General Survey Participants Perception on Reliability

The participants were asked about their average travel time to their work place. The average travel time of the 345 preliminary random general survey participants is 23.47 minutes. The United States Census Bureau reports that North Carolina's mean travel time to work is 23.6 minutes (Indexmundi, 2016). This implies that the collected sample is a good representation of North Carolina population.

The preliminary random general survey was designed to assess participants' perception on reliability; whether commuters choose a reliable route with higher travel time or unreliable route which has comparatively lower travel time (most of the times) than the reliable route. Figure 5 summarizes the perception of the participants and explains whether there is a correlation between income and route chosen (reliable vs. unreliable).

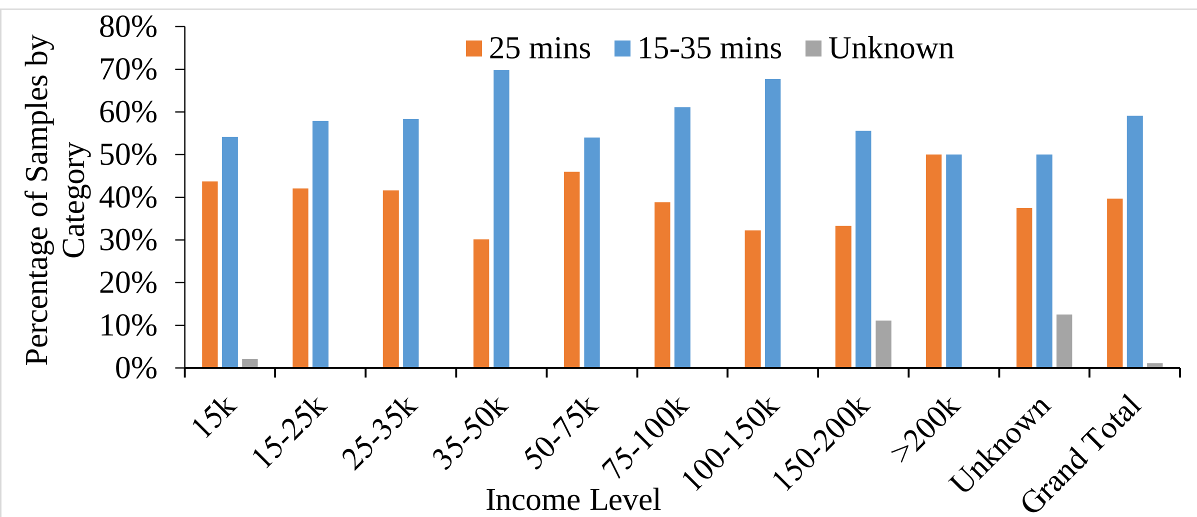


Figure 5. Route Chosen by Income Group - Preliminary Random General Survey

Most of the participants i.e., 55%, tend to prefer the unreliable route (travel time is lower most of the times than the travel time along the reliable route) over the reliable route. This implies that participants are willing to take the risk (choose an unreliable route) and save travel time on almost all but a few unexpected days when the maximum variation in travel time on unreliable route is not too high. No specific trend in the route chosen was observed with an increase in the participants' income. The average wage rate per minute of, both, who choose reliable route (25-minute travel time on all days) and unreliable route (travel time varies 15 to 35 minutes) is computed to be the same and equal to \$0.50 (\$30 per hour).

5.2. Additional Trip Time

The survey also consisted of questions that help evaluate how the road users plan their work trips. The additional time (beyond the average travel time) the participants planned to be on time is taken as the additional trip time. This additional trip time is not the same as buffer time (95th percentile travel time minus the average travel time) but could be considered as the maximum planned buffer time. It might include walking time to office from parking area, time spent to find a parking space, drop children at school or even time to grab breakfast / coffee on their way to work. A comparison of average travel time and additional trip time for different cities, towns and other areas in North Carolina is shown in Table 14.

Table 14. Comparison of Average Travel Time and Additional Trip Time by City, Town or Other Area

City, Town or Other Area	Average of Average Travel Time (Minutes)	Additional Trip Time to Daily Commute (Minutes)
Asheville	17.00	8.47
Charlotte	25.58	11.08
Greensboro	23.63	12.39
Raleigh	17.59	7.57
Other	26.51	11.58
Unknown	21.15	8.46
North Carolina	23.47	10.54

The average travel time for participants living in Charlotte (25.58 minutes) and other areas (26.51 minutes) is greater than the North Carolina's average travel time (23.47 minutes). Raleigh (17.59 minutes) and Asheville (17.00 minutes) participants reported the lowest average travel time. The computed average additional trip time for North Carolina is 10.54 minutes. Raleigh followed by Asheville have the lowest planned additional trip time compared to other locations; less than North Carolina's average additional trip time.

To account for unreliability during peak hours, road users plan additional trip time to be at their destination on time. This may depend on how important it is for them to be at their destination on time; example, if they are meeting their supervisors or inferiors during peak hours and off-peak hours. Therefore, participants were asked how they would plan their trip if they must meet their superior (important to be on time) vs. inferior (relatively not so important to be on time).

Survey results indicate that, the average additional trip time for a participant to meet an inferior (40.48 minutes) was less compared to the average additional trip time for meeting a superior (42.43 minutes) during peak hours. During off-peak hours, irrespective of who they are meeting, the average additional trip time was consistent (~38 minutes).

The Total Planned Trip Time (TPTT) and Additional Trip Time Index (ATTI) are defined using equations 12 and 13 and computed to assess variations in these metrics. Table 15 summarizes the computed TPTT and ATTI by city, town or other area during peak hours and off-peak hours.

$$\text{TPTT} = \text{Additional trip time} + \text{Average travel time} \qquad \text{Eq. 12}$$

$$\text{ATTI} = \frac{\text{Additional trip time}}{\text{Average travel time}} \qquad \text{Eq. 13}$$

Table 15. Average TPTT and ATTI by City, Town or Other Area

City, Town or Other Area	**Peak Hours**				**Off-Peak Hours**			
	Superior		**Inferior**		**Superior**		**Inferior**	
	TPTT	**ATTI**	**TPTT**	**ATTI**	**TPTT**	**ATTI**	**TPTT**	**ATTI**
Asheville	32.64	1.15	28.94	0.91	26.94	0.78	26.30	0.72
Charlotte	44.86	0.96	44.17	0.87	40.74	0.64	40.63	0.64
Greensboro	45.26	1.26	42.42	1.20	40.68	0.89	39.00	0.83
Raleigh	34.73	1.05	31.86	0.79	30.38	0.73	31.19	0.76
Other	45.85	1.06	44.24	0.96	43.66	0.79	43.75	0.76
Unknown	42.27	1.12	38.64	0.98	38.64	0.94	39.55	0.98
North Carolina	**42.43**	**1.06**	**40.48**	**0.93**	**38.61**	**0.75**	**38.45**	**0.74**

Greensboro participants reported the highest ATTI irrespective of the time of travel and importance of the trip (meet superior or inferior). TPTT is highest for Greensboro followed by Charlotte but lowest for Raleigh and Asheville irrespective of time period (peak or off-peak hours) and importance of the trip.

An effort was made to compare the variation in additional trip time with the hourly wage rate. Figure 6 shows the average additional trip time participants plan for their daily commute to work during morning peak hours by hourly wage rate (range).

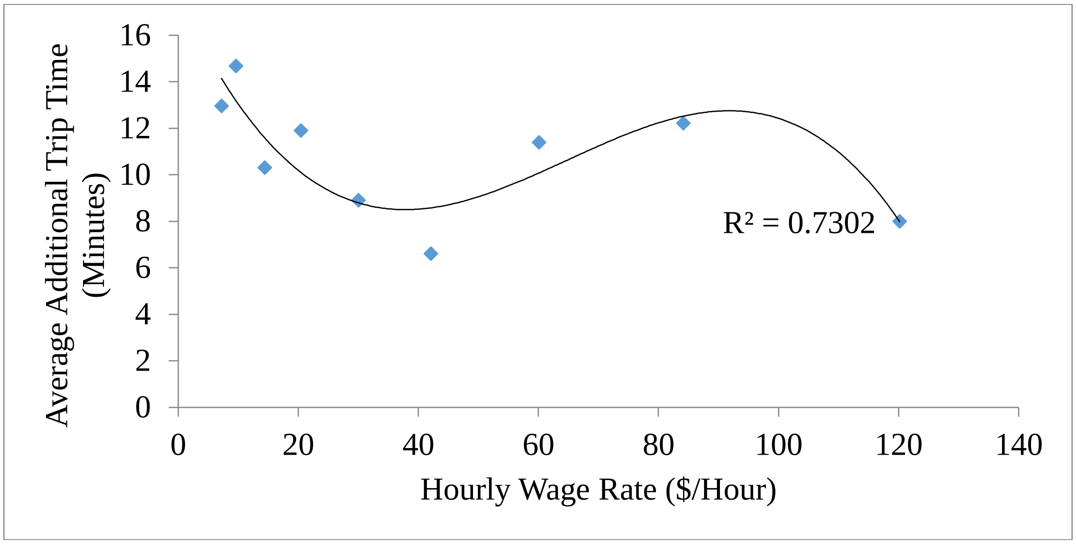


Figure 6. Average Additional Trip Time by Hourly Wage Rate

Low income participants were found to plan for higher additional trip time compared to medium and high income participants. This could be attributed to their working title and position, requiring them to be at work on time. High income participants were observed to plan for high additional trip time than medium income participants, implying their preference towards reliability and reaching destination on time.

Additional trip time may depend on the average travel time of a trip. To observe the relation between additional trip time and average travel time, the average travel time is grouped for every five minutes. The average additional trip time was then computed for each average travel time group (Figure 7).

Participants with an average travel time less than or equal to 5 minutes plan an average additional trip time of 6 minutes. For participants who travel 6 minutes to greater than 50 minutes, the additional trip time varied from 8 minutes to 14 minutes (excluding 46- to 50-minute travel time group). The trend is neither consistent nor clear though participants are planning for an additional trip time irrespective of their average travel time value.

The relationship between ATTI and hourly wage rate was also examined and compared in Figure 8. The figure indicates that low income participants opt for higher additional trip time compared to their average travel time, while medium income participants opt for a comparatively lower additional trip time compared to their average travel time. High income participants may not plan for high additional trip time but may value reliability.

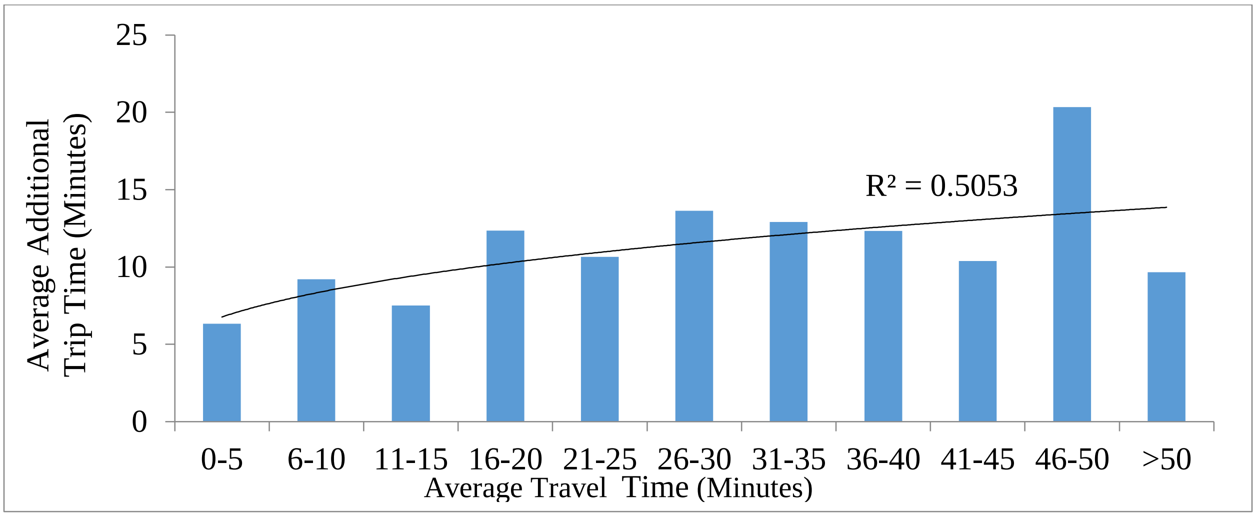


Figure 7. Average Additional Trip Time by Average Travel Time

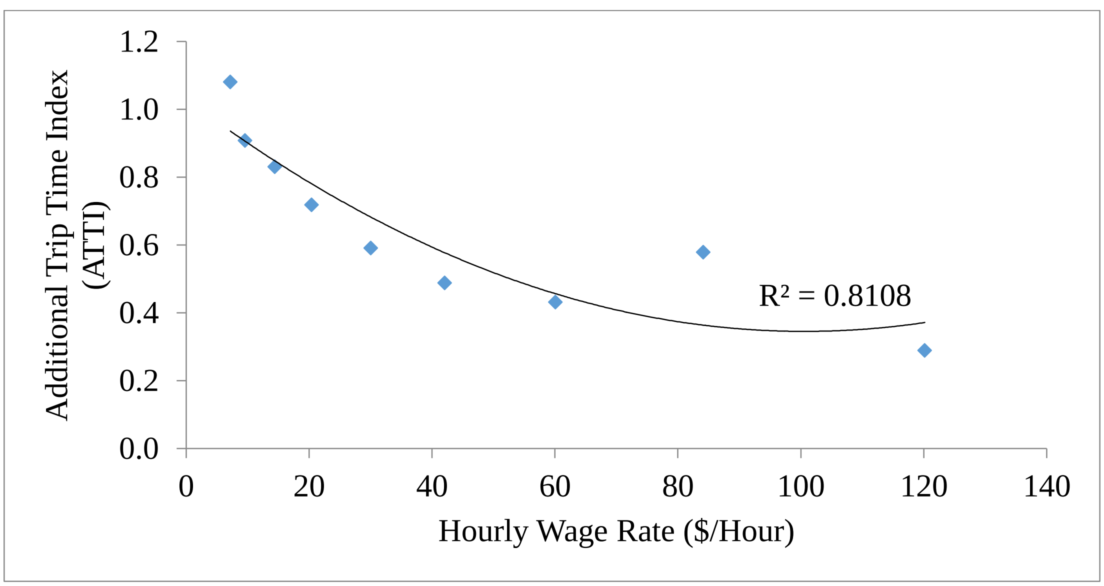


Figure 8. Relation between Hourly Wage Rate and Additional Trip Time Index

Analysis was also carried out to understand the relationship between the additional trip time and the hourly wage rate. Table 16 summarizes the average travel time, average additional trip time and ATTI by income group. Figure 9 summarizes the average travel time, average additional trip time and ATTI by hourly wage rate. From the figure, it is clear that middle-income group participants had the highest average travel time and the lowest additional trip time, whereas the low-income group participants have less average travel time (possibly live close to work) but high additional trip time.

Equations 14 and 15 can be used to estimate the average travel time and additional trip time, respectively if hourly wage rate (HWR) is known.

$$\text{Average Travel Time} = -0.0023\ \text{HWR}^2 + 0.3516\ \text{HWR} + 16.862 \qquad \text{Eq. 14}$$

$$\text{Additional Trip Time} = -1.449\ \ln(\text{HWR}) + 15.668 \qquad \text{Eq. 15}$$

Table 16. Average Travel Time and Additional Trip Time by Income Group

Income Level	Average of Average Travel Time (Minutes)	Average Additional Trip Time (Minutes)	Average ATTI
< $15,000	16.42	12.96	1.08
$15,000 - $25,000	24.79	14.68	0.91
$25,000 - $35,000	22.08	10.31	0.83
$35,000 - $50,000	22.72	11.91	0.72
$50,000 - $75,000	22.68	8.90	0.59
$75,000 - $100,000	24.78	6.61	0.49
$100,000 - $150,000	33.61	11.39	0.43
$150,000 - $200,000	30.00	12.22	0.58
> $200,000	25.56	8.00	0.29
Unknown	22.19	3.44	0.55
North Carolina	**23.47**	**10.54**	**0.72**

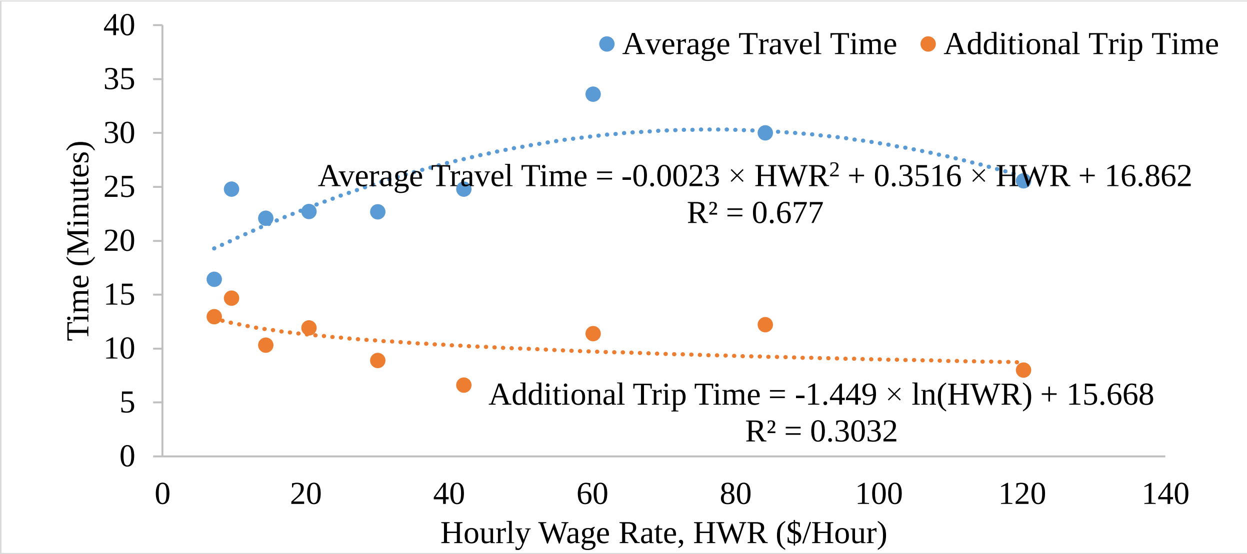


Figure 9. Variation of Average Travel Time, ATTI and Additional Trip Time with Hourly Wage Rate

5.3. Generalized Value of Travel Time and Travel Time Savings

The value of average travel time was first computed, for each participant of the preliminary random general survey, as the product of the participants' average travel time in minutes and wage rate per minute (hourly wage rate divided by sixty minutes). The value of average travel time was then summed for participants of each income group and divided by the sum of average travel time for participants of the same income group to compute the value of travel time per minute for that income group (Equation 16). Table 17 shows the computed value of travel time per minute for each income group. It can be observed that the value of average travel time per minute increased with the income group (as it is a function of income).

$$VTT_g = \frac{\sum_i^N \text{Average travel time}_{i,g} \times \text{Wage rate per minute}_{i,g}}{\sum_i^N \text{Average travel time}_{i,g}} \qquad \text{Eq. 16}$$

where, VTT_g is the value of average travel time, "i" is a participant and N is the total number of participants in income group "g".

Table 17. Value of Average Travel Time per Minute by Income Group

Income Group	Value of Average Travel Time per Minute
< $15,000	$0.12
$15,000 - $25,000	$0.16
$25,000 - $35,000	$0.24
$35,000 - $50,000	$0.34
$50,000 - $75,000	$0.50
$75,000 - $100,000	$0.70
$100,000 - $150,000	$1.00
$150,000 - $200,000	$1.40
> $200,000	$2.00

The computed value of average travel time per minute for each income group was then used to compute the generalized value of travel time per minute for North Carolina (Equation 17).

$$\text{Generalized Value of Travel Time} = \frac{\sum_g VTT_g \times P_g}{TP} \qquad \text{Eq. 17}$$

where,

VTT_g = Value of average travel time per minute for income group g,

P_g = Number of people living in North Carolina in income group g, and,

TP is total North Carolina population.

The generalized value of average travel time per minute for North Carolina is estimated equal to $0.51 per minute (~$30.60 per hour). This could also be used as the value of travel time savings per minute.

5.4. Generalized Value of Willingness to Pay

In the preliminary random general survey questionnaire, participants were also asked to provide information related to the amount they are willing to pay to reduce their travel time by 0-2 minutes, 2-5 minutes and 5-10 minutes. In general, the amount people are willing to pay may decrease with the increase in possible travel time savings.

From the responses for these three questions on willingness to pay, an average willingness to pay to reduce one minute of travel time was estimated as a function of their wage rate per minute for each income group. Table 18 shows the value of willingness to pay to reduce one minute of travel time by income group.

Table 18. Comparison of Willingness to Pay by Income Group

Income Group	Value of Willingness to Pay per Minute			
	Response to "<2 Minutes"	Response to "2-5 Minutes"	Response to "5-10 Minutes"	Average Response
< $15,000	0.15	0.08	0.09	0.12
$15,000 - $25,000	0.21	0.10	0.08	0.14
$25,000 - $35,000	0.15	0.08	0.07	0.11
$35,000 - $50,000	0.19	0.10	0.06	0.12
$50,000 - $75,000	0.16	0.07	0.06	0.11
$75,000 - $100,000	0.11	0.07	0.05	0.08
$100,000 - $150,000	0.12	0.06	0.07	0.10
$150,000 - $200,000	0.32	0.14	0.08	0.18
> $200,000	0.14	0.10	0.08	0.11
Unknown	0.12	0.05	0.04	0.08

The value of willingness to pay was observed not to vary with the income group. The highest value of willingness to pay was observed for the $15,000-$25,000 income group (possibly due to their need to be not late to work), while the lowest value of willingness to pay was observed for $75,000-$100,000 income group.

The computed value of willingness to pay to reduce one minute of travel time for each income group was then used to compute the generalized value of willingness to pay for North Carolina (Equation 18).

$$\text{Generalized Value of Willingness to Pay} = \frac{\sum_g \text{VWP}_g \times \text{P}_g}{\text{TP}} \qquad \text{Eq. 18}$$

where,

VWP_g = Value of willingness to pay to reduce one minute of travel time for income group g,

P_g = Number of people living in North Carolina in income group g, and,

TP is total North Carolina population.

The generalized value of willingness to pay to reduce one minute of travel time for North Carolina is estimated equal to \$0.11 per minute (~\$6.60 per hour).

5.5. Generalized Value of Additional Trip Time

The value of additional trip time participants are planning to reach their destination on time for a typical work day trip was also estimated using preliminary random general survey data. Participants average travel time and at what time they would leave if they must be at work by 8:00 AM was used to estimate additional trip time for their daily commute.

For example, the average travel time for a participant might be 15 minutes. The participant might leave around 7:35 AM to be at work by 8:00 AM. This implies that the participant plans for an additional 10 minutes to make sure he/she reaches work on time. The value of 10 minutes is his/her value of additional trip time.

The value of additional trip time was computed, for each participant of the preliminary random general survey, as the product of the participants' additional trip time in minutes and wage rate per minute. The value of additional trip time was then summed for participants of each income group and divided by the sum of additional trip time for participants of the same income group to compute the value of additional trip time per minute for that income group (Equation 19).

$$\mathrm{VATT_g} = \frac{\sum_{i}^{N} \text{Additional trip time}_{i,g} \times \text{Wage rate per minute}_{i,g}}{\sum_{i}^{N} \text{Additional trip time}_{i,g}} \qquad \text{Eq. 19}$$

where, $\mathrm{VATT_g}$ is the value of additional trip time, "i" is participant, and N is the total number of participants in income "g".

Table 19 shows the computed value of additional trip time per minute by income group. In general, the value of additional trip time per minute increases with the hourly wage rate.

The value of additional trip time per minute for each income group was used to estimate the generalized value of additional trip time per minute for North Carolina population (Equation 20).

$$\text{Generalized Value of Additional Trip Time} = \frac{\sum_{g} \mathrm{VATT_g} \times \mathrm{P_g}}{\mathrm{TP}} \qquad \text{Eq. 20}$$

where,

$VATT_g$ = Value of additional trip time per minute for income group g,

P_g = Number of people living in North Carolina in that income group g, and,

TP is total North Carolina population.

Table 19. Comparison of Value of Additional Trip Time per Minute by Income Group

Income Group	Value of Additional Trip Time per Minute
< $15,000	$0.12
$15,000 - $25,000	$0.16
$25,000 - $35,000	$0.24
$35,000 - $50,000	$0.34
$50,000 - $75,000	$0.50
$75,000 - $100,000	$0.70
$100,000 - $150,000	$1.00
$150,000 - $200,000	$1.40
> $200,000	$2.00

The generalized value of additional trip time per minute is estimated equal to $0.51 ($30.6 per hour) for North Carolina. This value is greater than what participants are willing to pay ($0.11 per minute or $6.60 per hour). This implies that participants would benefit more due to higher consistency in travel time than what they are willing to pay for reduced travel time on any given route. The additional trip time may include components other than planned additional time to be spent on road while driving. In other words, the actual buffer time (difference between 95th percentile travel time and average travel time) is less than or equal to the additional trip time.

A comparison was made between gender and age groups to examine how the value of additional trip time per minute varies among different groups. Tables 20 and 21 summarize the value of additional trip time per minute by gender and age group, respectively. The generalized values shown in the tables are computed by considering population by gender and age group, respectively.

Females value the additional trip time lower when compared to males. The value of additional trip time per minute was observed to increase as the age increases.

Table 20. Value of Additional Trip Time per Minute by Gender

Gender	Value of Additional Trip Time per Minute
Male	$0.49
Female	$0.38
North Carolina (Generalized)	$0.44

Table 21. Value of Additional Trip Time per Minute by Age Group

Age Group	Value of Additional Trip Time per Minute	Average Hourly Wage Rate	Average of Average Travel Time (Minutes)	Average Additional Trip Time (Minutes)	Average ATTI
20-34	$0.29	$19.97	22.77	10.48	0.76
35-55	$0.65	$46.48	25.69	10.55	0.62
56-75	$0.61	$31.57	18.74	11.00	0.90
North Carolina (Generalized)	$0.53	$30.54	23.47	10.54	0.72

A generalized value of additional trip time per minute was estimated taking gender and age groups into consideration (similar to Equation 20). The generalized value of additional trip time per minute by gender is $0.44. Similarly, the generalized value of additional trip time per minute by age group is $0.53.

To observe the reason for the low value of additional trip time per minute for age group 20-34, additional analysis was carried out between additional trip time and hourly wage rate by age group (as the value of additional trip time per minute is a function of both these variables). Participants in 35-54 years age group had the highest hourly wage rate compared to the other two age groups. The lowest hourly wage rate was for participants with age between 20-34 years. This might be the reason for the low value of additional trip time per minute for this age group. Further, the variation in additional trip time and ATTI by age group was also compared. From Table 21, it can be observed that participants between 20-34 years had the highest ATTI. They are followed by 55-75 years age group. Participants in the middle age group are the ones that have lower additional trip time even though they have higher average travel time (travel longer distances or duration).

As mentioned earlier, the participants were also asked how they would plan their trip, if they must meet their superiors or inferiors during peak hours and off-peak hours. As the value of additional trip time per minute is a function of additional trip time and wage rate per minute, the value of additional trip time per minute also changes with additional trip time. The additional trip time participants opt during peak hours is different from off-peak hours. Therefore, the value of additional trip time per minute is estimated for both peak hours and off-peak hours separately. Table 22 summarizes the value of additional trip time per minute estimated by age group for peak hours and off-peak hours.

Table 22. Value of Additional Trip Time during Peak and Off-Peak Hours by Age Group

Age Group	**Value of Additional Trip Time per Minute**	
	Peak Hours	**Off-Peak Hours**
20-34	$0.33	$0.33
35-54	$0.72	$0.75
55-75	$0.50	$0.57
North Carolina (Generalized)	$0.54	$0.57

A significant difference between the value of additional trip time per minute during peak hours and off-peak hours was observed for age group 55-75 years. For the whole sample, the value of additional trip time per minute is $0.51. This is lower than the value of additional trip time per minute during peak hours ($0.54) as well as off-peak hours ($0.57). To better understand the relationship, the value of additional trip time per minute for peak hours and off-peak hours was estimated for different income groups. Table 23 summarizes the value of additional trip time per minute by income group. A generalized value of additional trip time per minute was estimated for North Carolina separately for peak hours and off-peak hours. The computed generalized value of additional trip time per minute is higher for peak hours ($0.67) than off-peak hours ($0.40).

As mentioned previously, the value of additional trip time per minute may vary by city, town or other area. Therefore, the average value of additional trip time per minute was also computed by city, town and other area and summarized in Table 24. The value of additional trip time per minute is lowest for Asheville followed by Raleigh and Greensboro. The highest value of additional trip time per minute is observed for Charlotte ($0.67).

The value of additional trip time per minute is a function of both additional trip time and wage rate per minute. From Table 15, the average additional trip time for participants of Asheville and Raleigh is comparatively lower than the average for North Carolina. This might be the reason for lower value of additional trip time per minute for these two cities. To understand the reason behind the large difference in the value of additional trip time per minute, average hourly wage rate by city, town or other area are computed and shown in Table 24.

Table 23. Value of Additional Trip Time per Minute during Peak and Off-Peak Hours by Income Group

Income Group	Value of Additional Trip Time per Minute	
	Peak Hours	Off-Peak Hours
< $15,000	$0.12	$0.12
$15,000 - $25,000	$0.16	$0.16
$25,000 - $35,000	$0.24	$0.24
$35,000 - $50,000	$0.34	$0.34
$50,000 - $75,000	$0.50	$0.50
$75,000 - $100,000	$0.70	$0.70
$100,000 - $150,000	$1.00	$1.00
$150,000 - $200,000	$1.40	$1.40
> $200,000	$2.00	$2.00
North Carolina (Generalized)	0.51	0.51

Table 24. Value of Additional Trip Time per Minute by Cities, Towns and Other Areas

City, Town or Other Area	Value of Additional Trip Time per Minute	Average Hourly Wage Rate
Asheville	$0.25	$22.74
Charlotte	$0.62	$35.78
Greensboro	$0.19	$15.60
Raleigh	$0.28	$21.92
Other	$0.49	$36.95
Unknown	$0.48	$37.59

Per 2013 census data, the average annual income for North Carolina is $46,657. Converting into hourly wage rate using state's average, the average hourly wage rate for North Carolina is $24.30. This is less than the average hourly wage rate of the sample ($30.54). This is because the survey was carried out at gas stations and people not owning a car will not be using the gas stations. Tables 15 and 24 explain the reasons for such variations in the value of additional trip time per minute by city, town or other area.

Chapter 6. Focus Group Survey Results

Nine focus group meetings were conducted as a part of this project task. The major difference between the focus group and preliminary random general survey is that the focus group participants were given a 10- to 15-minute presentation explaining the concept of reliability and the need for conducting the project. The participants were then given a chance to review the questionnaire regarding the concept and ask any questions. Once they are clear, they were asked to complete the survey questionnaire. Table 25 shows the number of samples collected at each focus group meeting.

Table 25. Number of Participants from Each Focus Group Meeting

Focus Group Meeting Title	Number of participants
Charlotte Department of Transportation Planning Division	9
Charlotte Piedmont Community College	9
Mecklenburg County Air Quality Division	6
North Carolina Department of Transportation	21
Energy Production and Infrastructure Center, UNC Charlotte	8
North Carolina Rail Museum	11
University of North Carolina at Asheville	11
Random-Greensboro	7
Random-NCSITE	11
Grand Total	93

The focus group coordinating staff made sure that each focus group meeting comprised of staff at different levels (position, income, etc.) within the meeting participants. Table 26 represents the focus group samples collected by age and gender. Most focus group participants are in the age group of 35-55 years, while 68% of the focus group participants are male. Table 27 summarizes the percent of focus group participants by income group.

Table 26. Samples Collected by Age and Gender - Focus Group Survey

Gender	Age Group				Grand Total
	20-34	35-55	56-75	>75	
Male	15	32	14	2	63
Female	4	20	6	-	30
Grand Total	19	52	20	2	93

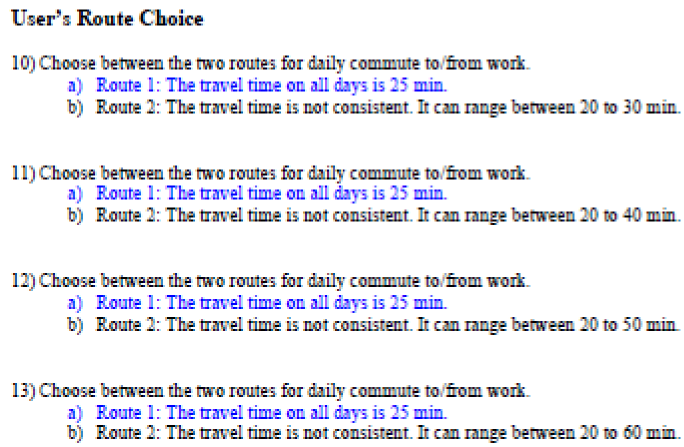
Table 27. Focus Group Participants by Income group

Income Group	% of Participants
< $15,000	0%
$15,000 - $25,000	2%
$25,000 - $35,000	8%
$35,000 - $50,000	13%
$50,000 - $75,000	32%
$75,000 - $100,000	20%
$100,000 - $150,000	16%
$150,000 - $200,000	3%
> $200,000	4%
Unknown	1%
Grand Total	100%

6.1. Focus Group Participants Perception on Reliability

Like route choice question in preliminary random general survey, the participants were asked to choose between a reliable route and unreliable route. The questions were designed to observe participants' trade-off between consistency in travel times (reliability) and possible travel time savings.

Figure 10 summarizes the questions and an example participants' selection between route 1 (with 25-minute travel time on all days) and route 2 (unreliable route). Figure 11 summarizes how sensitive focus group participants are to reliability of transportation system (difference between possible maximum and minimum travel time). Among all the participants, 56% have chosen reliable route, whereas the remaining 44% were willing to take the risk of getting delayed to save 5 minutes of their travel time. There is a significant decrease in the number of participants choosing unreliable route as the variation in travel time increased. This is primarily because, to save 5 minutes of travel time, they need to take a risk of getting delayed by 30 or 40 minutes.



User's Route Choice

10) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days is 25 min.
   b) Route 2: The travel time is not consistent. It can range between 20 to 30 min.

11) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days is 25 min.
   b) Route 2: The travel time is not consistent. It can range between 20 to 40 min.

12) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days is 25 min.
   b) Route 2: The travel time is not consistent. It can range between 20 to 50 min.

13) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days is 25 min.
   b) Route 2: The travel time is not consistent. It can range between 20 to 60 min.

Figure 10. Sample Response of a Participant on Route Choice by Travel Time

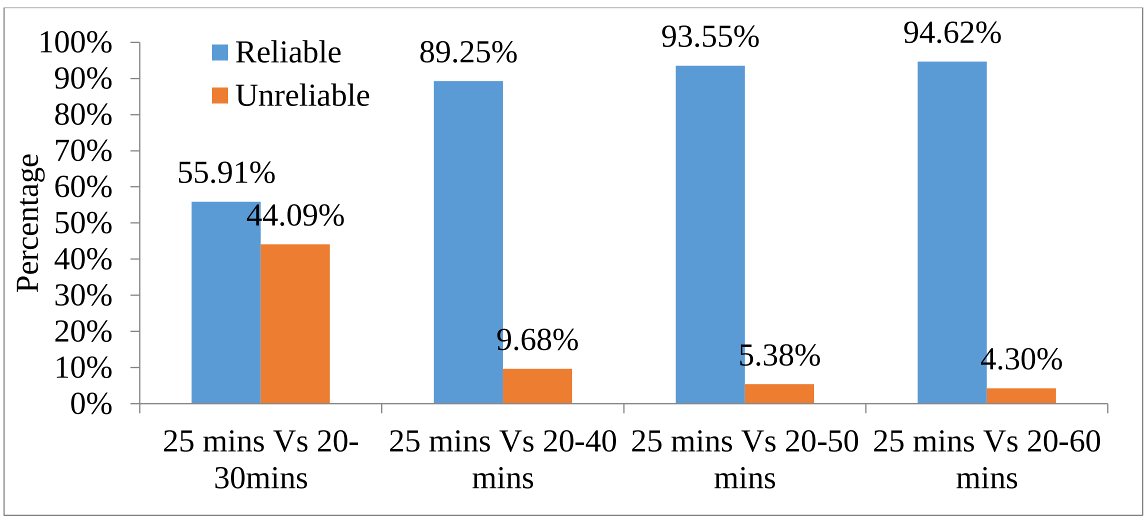


Figure 11. Route Chosen by Participants - Focus Group Survey

Besides the variation in travel time, the number of times travel time varies during a month also plays a key role in road users' route choice decision. To capture such information, the participants were asked to choose between a reliable route (with a 25-minute travel time on all days) and unreliable route (20-minute travel time on most days and on 'x' days a month it might be 35 minutes). The questions and an example participants' selection of routes is summarized in Figure 12. As the number of days of unreliability increases (given 2, 4, 6, and 8 in the questionnaire), the road users are expected to shift to a reliable route to avoid more frequent inconsistency. There might be a few users who are willing to forego travel time savings and choose the reliable route all the time.

User's Perspective on Reliability

6) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days during a month (20 working days) is 25 min.
   b) Route 2: The travel time on most of the days is 20 min, whereas on 2 unexpected days out of 20 working days it is 35 min.

7) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days during a month (20 working days) is 25 min.
   b) Route 2: The travel time on most of the days is 20 min, whereas on 4 unexpected days out of 20 working days it is 35 min.

8) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days during a month (20 working days) is 25 min.
   b) Route 2: The travel time on most of the days is 20 min, whereas on 6 unexpected days out of 20 working days it is 35 min.

9) Choose between the two routes for daily commute to/from work.
   a) Route 1: The travel time on all days during a month (20 working days) is 25 min.
   b) Route 2: The travel time on most of the days is 20 min, whereas on 8 unexpected days out of 20 working days it is 35 min.

Figure 12. Sample Response of a Participant on Route Choice by Number of Days of the Lack of Reliability

Figure 13 summarizes how sensitive focus group participants are to the number of days they can tolerate unreliability. Most participants are willing to tolerate two to four days of unreliability or inconsistency in travel time during a month (~one day per week). Less than 16% of participants are willing to tolerate the lack of reliability for more than one day per week. In general, as the number of days of unreliability increased per month, participants started shifting from an unreliable route to a reliable route.

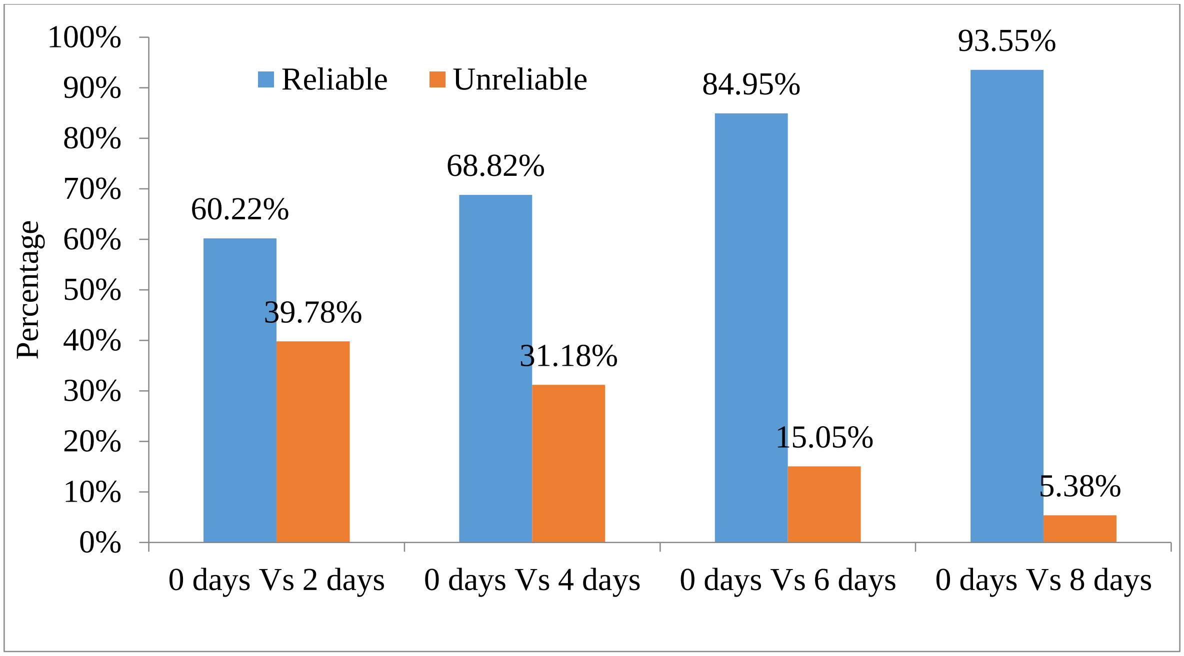


Figure 13. Route Chosen by Participants - Focus Group Survey

6.2. Generalized Value of Buffer Time (BT) from Focus Group Survey Participants Data

The buffer time of a focus group participant is the additional trip time he/she is willing to accept by selecting an unreliable route over a reliable route (expecting to minimize travel time and save time for most of the trips). The difference between the acceptable maximum travel time along the unreliable route and travel time along the reliable route is considered as buffer time. The value of buffer time is defined as the value of this difference and is computed for each participant as a function of the participants' wage rate per minute and his/her buffer time.

As an example, consider a participant who is willing to accept an unreliable route with a maximum travel time of 35 minutes instead of a reliable route with a travel time of 25 minutes. If the unreliability increased and maximum travel time exceeds 35 minutes, he/she would shift to the reliable route. The planned or acceptable buffer time for this participant is 10 minutes. If the participants' hourly wage rate is $30, the value of 10-minute buffer time for this participant is $5.

The value of buffer time was computed for each participant of the focus group survey as the product of the participants' buffer time in minutes and wage rate per minute. The value of buffer time was then summed for participants of each income group and divided by the sum of buffer time for participants of the same income group to compute the value of buffer time per minute for that income group (Equation 21).

$$\text{VBT}_g = \frac{\sum_i^N \text{Buffer time}_{i,g} \times \text{Wage rate per minute}_{i,g}}{\sum_i^N \text{Buffer time}_{i,g}} \qquad \text{Eq. 21}$$

where, VBT_g is the value of buffer time, "i" is participant, and N is the total number of participants in income "g".

None of the focus group survey participants earned less than $15,000/year. Table 28 summarizes the value of buffer time per minute by income group. The average value of buffer time generally increased with participants' income group.

Table 28. Value of Buffer Time per Minute by Income - Focus Group Survey

Income Group	Value of Buffer Time per Minute
< $15,000	-
$15,000 - $25,000	$0.16
$25,000 - $35,000	$0.24
$35,000 - $50,000	$0.34
$50,000 - $75,000	$0.50
$75,000 - $100,000	$0.70
$100,000 - $150,000	$1.00
$150,000 - $200,000	$1.40
> $200,000	$1.80

The value of buffer time per minute for each income group was used to estimate the generalized value of buffer time per minute for North Carolina population (Equation 22).

$$\text{Generalized Value of Buffer Time} = \frac{\sum_g \text{VBT}_g \times \text{P}_g}{\text{TP}} \qquad \text{Eq. 22}$$

where,

VBT_g = Value of BT per minute for income group g,

P_g = Number of people living in North Carolina in that income group g, and,

TP is total North Carolina population.

The generalized value of buffer time per minute is estimated equal to $0.48 ($28.80 per hour). This value is lower when compared to wage rate per minute ($0.66) of those focus group survey participants who only preferred the reliable route (buffer time is zero). It is also less than the value of additional trip time per minute (\$0.51) from the preliminary random general survey.

Chapter 7. Final Random Survey Results

The samples from focus group survey participants are primarily from offices and participants with similar educational qualifications. Also, at least 40% of the focus group survey sample is directly or indirectly associated with the transportation sector. The participation from people working in the private industry (grocery stores, Research Triangle Park area, banking sector in the Charlotte region, etc.) is not adequate. The employers were not willing to let their employees participate in focus group survey meetings. Furthermore, most of the focus group survey participants are in the 35-55 year age group. Female participants are found to be less than 35%. While 40% of North Carolina population earns less than $35,000, the sample from focus group survey participants is not even 10% in this income group. Likewise, the sample from high income group (>= $150,000) is also not representative. Therefore, the data collected through focus groups is not a good representation of the North Carolina population.

Unlike focus group survey, the preliminary random general survey represented a better distribution of samples. Some of the questions aimed to capture the value of reliability, buffer time and tolerance towards the number of unreliable days from focus group meetings were not captured in the preliminary random general survey. Therefore, another round of random survey using the focus group survey questionnaire was conducted to achieve better results in estimating the value of reliability.

The methodology to collect the samples in case of final random survey is similar to the preliminary random general survey. Students standing at gas stations that were randomly chosen across the city or towns asked the people who were using the gas stations if they were willing to participate in the survey. A total of 357 samples were collected across four cities and towns in North Carolina. A few samples were ignored from analysis as participants' input was not clear and did not follow the expected trend. After removing such outliers, a total of 334 samples were used for analysis. Table 29 shows the samples collected by age and gender. Table 30 shows the samples collected by income level.

Like in the preliminary random general survey, the female participation in the final random survey was less compared to males. Majority of the participants are in the age group of 35-55 years. A considerable number of samples were obtained in all income groups except the income level greater than $200,000. In North Carolina, around 3.3% of the total population belong to this high-income level.

Table 29. Number of Samples Collected by Age and Gender - Final Random Survey

Gender	Age Group				Grand Total
	20-34	35-55	56-75	> 75	
Male	69	85	50	4	208
Female	45	61	18	2	126
Grand Total	114	146	68	6	334

Table 30. Samples Collected by Income Group - Final Random Survey

Income Level	Number of Participants	% of Participants
< $15,000	31	9.3%
$15,000 - $25,000	37	11.1%
$25,000 - $35,000	15	4.5%
$35,000 - $50,000	78	23.3%
$50,000 - $75,000	81	24.2%
$75,000 - $100,000	67	20.1%
$100,000 - $150,000	14	4.2%
$150,000 - $200,000	5	1.5%
> $200,000		-
Unknown	6	1.8%
Grand Total	334	100.0%

7.1. Final Random Survey Participants Perception on Reliability

Like route choice questions in focus group survey, the participants were asked to choose between a reliable route and unreliable route. The questions were designed to observe participants' trade-off between consistency in travel times (reliability) and possible travel time savings. The number of participants who were willing to choose a reliable route over unreliable route was used in evaluations. Samples in which users shifted from a reliable to unreliable route were considered as outliers (inaccurate information if the participant was in a hurry and / or lacked proper understanding of the concept).

Among all the participants, ~40% have chosen the reliable route, whereas the remaining 60% were willing to take the risk of getting delayed to save 5 minutes of their travel time (more than what was observed in case of focus group survey participants). There was a considerable decrease in the number of participants choosing unreliable route as the variation in travel time increased. This is similar to what was observed in case of focus group survey. Figure 14 summarizes participants' preference towards reliability based on variation in travel time.

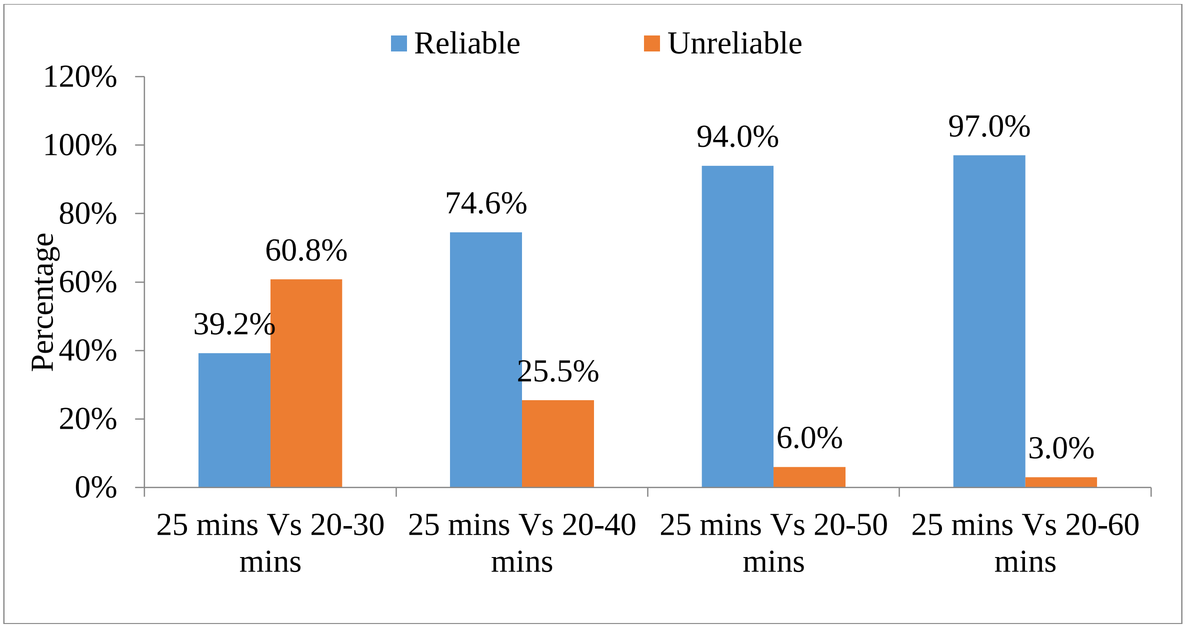


Figure 14. Route Chosen by Users Based on the Duration of Unreliability - Final Random Survey

The participants were also asked to choose between a reliable route (with 25-minute travel time on all days) and unreliable route (20 minutes travel time on most days and on 'x' days it might be 35 minutes). As the number of days of unreliability increases (given 2, 4, 6, and 8 in the questionnaire), the road users may not find consistent travel time savings and are expected to shift to a reliable route. Figure 15 summarizes the sensitivity of participants towards the tolerance of unreliability (number of days of the lack of reliability per month). Around 60% of the overall participants were willing to accept the unreliable route for two days. This is because they are willing to take the risk of getting late on two days to save travel time on the other 18 days in a month. As the unreliability increased, the percentage of people choosing unreliable route reduced. Around 40% of the total participants are not willing to tolerate even two days of unreliability per month.

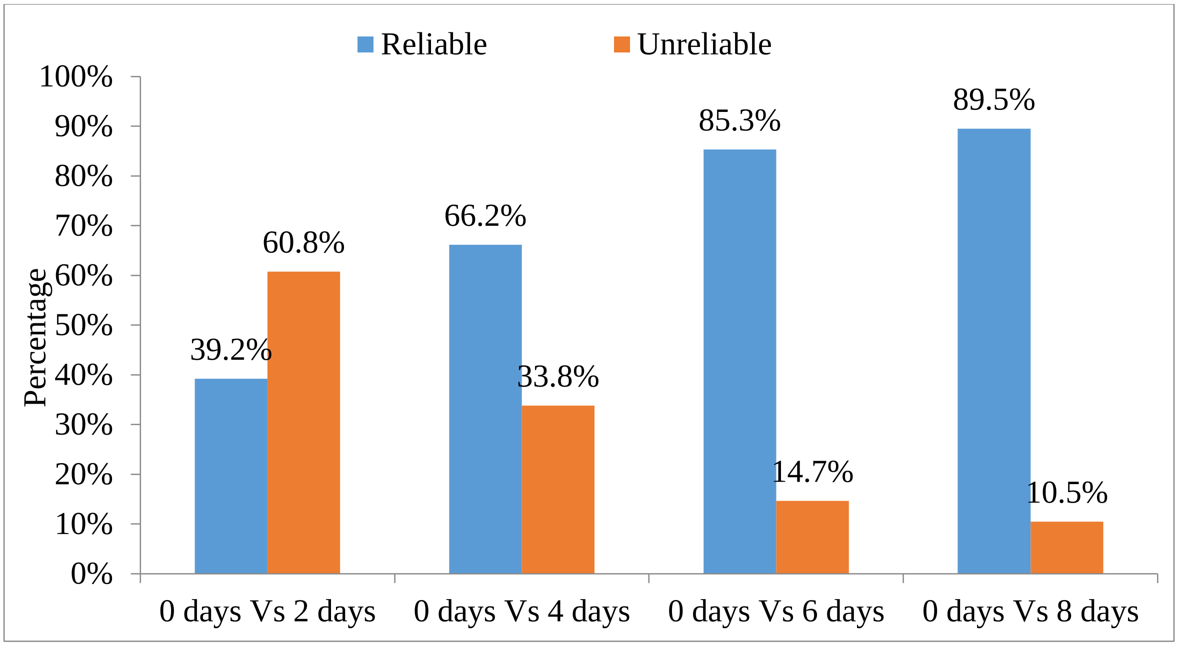


Figure 15. Route Chosen by Users Based on Number of days of Unreliability - Final Random Survey

The interpretations shown in Table 31 can be drawn based on tolerance limits of the drivers observed from Figure 14 and Figure 15 towards the reliability on roads. These results can be used to identify the tolerance limits of drivers related to reliability on roads. From Table 31, more than 65% of road users has a maximum tolerance limit of 4 days of unreliability for work trips during a month. Similarly, 75% of road users accept a maximum severity of 20 minutes of additional time to work for up to 4 days in a month.

Table 31 Tolerance Limits for Drivers from this Study

Variable	Tolerance Limit	% Tolerable
Frequency	4 days in a month	33.8%
Severity	20 minutes for a 20-minute trip	25.5%

7.2. Generalized Value of Buffer Time from Final Random Survey Participants Data

Like the focus group survey, the value of buffer time was computed for each final random survey participant. The value of buffer time was then summed for participants of each income group and divided by the sum of buffer time for participants of the same income group to compute the value of buffer time per minute for that income group (using Equation 21). Table 32 summarizes the average value of buffer time by income group based on final random survey data. Using Equation 22, the generalized value of buffer time per minute was then computed.

The generalized value of buffer time per minute based on final random survey data is estimated equal to $0.45 ($27.00 per hour). This is marginally lower than the generalized value of buffer time per minute from the focus group survey data. This value is also marginally lower when compared to wage rate per minute ($0.46) of those participants who only preferred the reliable route (buffer time is zero).

The variation in the value of reliability by city, town or other area is shown in Table 33. Asheville followed by Greensboro has the lowest value of buffer time per minute based on final random survey data. They are lower than North Carolina's average value of buffer time ($0.45 per minute). The participants' value of buffer time is highest and greater than North Carolina's generalized value for Charlotte.

Table 32. Value of Buffer Time per Minute by Income Level - Final Random Survey

Income Level	Value of Buffer Time per Minute
< $15,000	$0.05
$15,000 - $25,000	$0.16
$25,000 - $35,000	$0.19
$35,000 - $50,000	$0.36
$50,000 - $75,000	$0.54
$75,000 - $100,000	$0.76
$100,000 - $150,000	$1.09
$150,000 - $200,000	$1.52
> $200,000	-

Table 33. Value of Buffer Time per Minute by City, Town or Other Area - Final Random Survey

City, Town or Other Area	Value of Buffer Time per Minute
Asheville	$0.28
Charlotte	$0.51
Greensboro	$0.35
Raleigh	$0.51

7.3. Reliability Thresholds

Along with the respective values for travel times, buffer times etc., the tolerance levels of the road users towards unreliability of roads in the transportation network will help agencies prioritize the segments for any improvements. The reliability thresholds were evaluated based on the responses for the focus group survey and final random survey. Table 34 shows the reliability threshold based on the buffer time. The first column shows the thresholds based on the average travel time of a 25-minute trip to/from work. The second column helps evaluate the threshold limits for any route/trip based on the percentage of average travel time. The results obtained indicate that roads segments with 20% of additional travel time is highly acceptable and these segments can be considered as highly reliable, whereas the segments with additional travel time of more than 60% of average travel time are considered as unreliable road segments. Similarly, from Table 35, road users are willing to tolerate up to 2 days of unreliability in a month and are extremely intolerant for more than 4 days of unreliability in a month. Therefore, the lack of reliability for one or two days per month is considered as highly reliable, 3 or 4 days per month is considered as moderately reliably, and more than 4 days per month is unreliable.

Table 34. Reliability Thresholds Based on Buffer Time

Based on Average Travel Time of 25 Minutes	Percentage of Average Travel Time	Reliability
≤ 5 Minutes	≤ 20%	Highly Reliable
> 5 Minutes & ≤ 15 Minutes	> 20% & ≤ 60%	Moderately Reliable
> 15 Minutes	> 60%	Unreliable

Table 35. Reliability Thresholds Based on Number of Days of Unreliability

No. of Days Unreliable in a Month	Reliability
≤ 2 Days	Highly Reliable
> 2 Days & ≤ 4 Days	Moderately Reliable
> 4 Days	Unreliable

Chapter 8. Illustration and Applicability of Results

NCDOT, regional agencies, cities, towns and local municipalities design and maintain transportation system for the benefit of road users by improving mobility, reducing travel time and enhancing safety. Cost-benefit analysis helps these agencies in prioritizing a project / transportation alternative or when evaluating transportation alternatives. The processes help the agencies efficiently and effectively use the limited available resources.

In the cost-benefit analysis, the effect and impact of various transportation projects or alternatives are monetized to evaluate and make improved decisions. The illustration and applicability of evaluating the reliability and the value of reliability to assist with such decisions is presented in this Chapter.

8.1. Reliability by Time-of-the-Day

The reliability of a link or segment could vary based on the time-of-the-day. As stated previously, the possibility of capturing extensive, continuous, and dynamic travel time data from private sources such as HERE, INRIX and Tom Tom opened many pragmatic avenues to predict reliability at link-level by time-of-the-day.

Data from INRIX for the year 2011 was used to illustrate the reliability of the links by time-of-the-day and day-of-the-week. As explained in Chapter 3, average travel time and 95th percentile travel time were computed by time-of-the-day and day-of-the-week for road links in the Charlotte metropolitan area. For illustration purpose, a 2.1-mile segment on I-77 northbound at Harris Oak Blvd/Reames Rd/Exit 18 intersection and a 3.6-mile segment on I-77 northbound at Gilead Rd/Exit 23 intersection in the City of Charlotte area are considered.

Figure 16 shows the comparison of average travel time and 95th percentile travel time for the 2.1-mile segment on I-77 northbound at Harris Oak Blvd/Reames Rd/Exit 18 intersection. The buffer time is the difference between 95th percentile travel time and average travel time at any given time-of-the-day. From Figure 16, the 95th percentile travel times are always greater than the average travel times, irrespective of time-of-the-day and day-of-the-week. This indicates that the segment is unreliable during all times of the day and days of the week.

Figure 17 shows the comparison of average travel times and 95th percentile travel times for the 3.6-mile segment on I-77 northbound at Gilead Rd/Exit 23 intersection. From figure 17, the

95th percentile travel times are always equal to the average travel times, except during evening peak hours from Monday through Saturday. Whereas, the 95th percentile travel times are equal to the average travel times during any time-of-the-day on Sundays. This indicates that the segment is unreliable only during evening peak hours from Monday through Saturday and completely reliable on Sundays.

The reliability (total buffer time) of the link during a day-of-the-week can be evaluated from the area between the average travel time and 95th percentile travel time curves in figures 16 and 17. For illustration, Figure 18 shows the area between the average travel time and 95th percentile travel time for the 2.1-mile segment on I-77 northbound at Harris Oak Blvd/Reames Rd/Exit 18 intersection on Mondays.

The buffer time between the curves during a peak hour (8:00 am to 9:00 am) is 15 seconds. Multiplying the buffer time with traffic volume between 8:00 am to 9:00 am (assume 6,000 vehicles) will give the total buffer time (1,500 minutes) during the considered peak period. Multiplying the total buffer time with the generalized value of reliability ($0.45 per minute) will help evaluate the total value of unreliability ($600) during the considered peak hour.

In case of availability of hourly traffic volumes for the entire day, area between plot similar to Figure 18 with hourly traffic volumes on x-axis and buffer times on y-axis will directly give the total buffer time for the time period considered. Multiplying the total buffer time with generalized value of reliability will help monetize the value of reliability for the road segment considered by time-of-the-day and day-of-the-week.

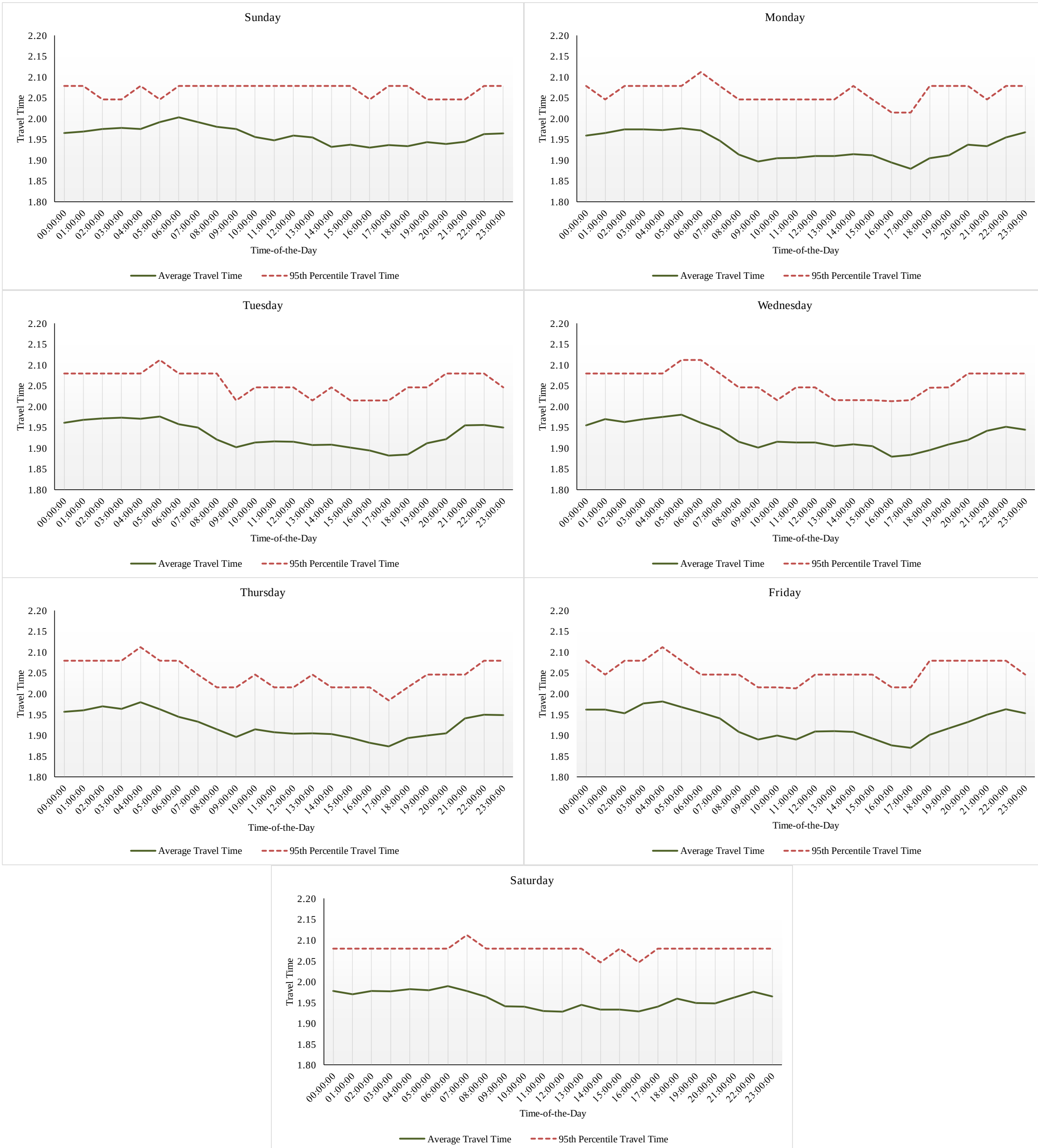


Figure 16. Illustration of Segment that is Unreliable during All Times of the Day and Days of the Week

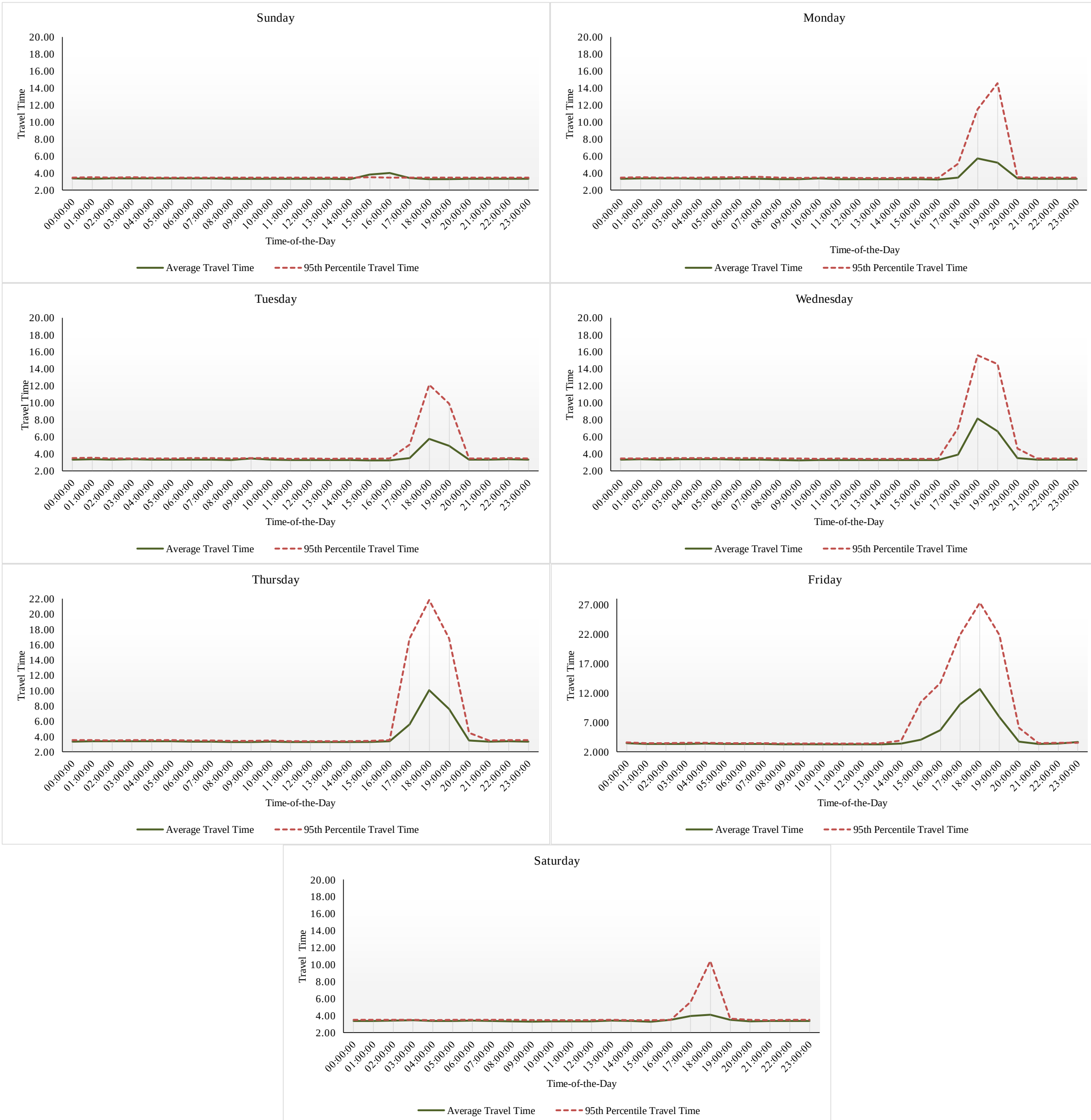


Figure 17. Illustration of Segment that is Unreliable during Evening Peak Hours

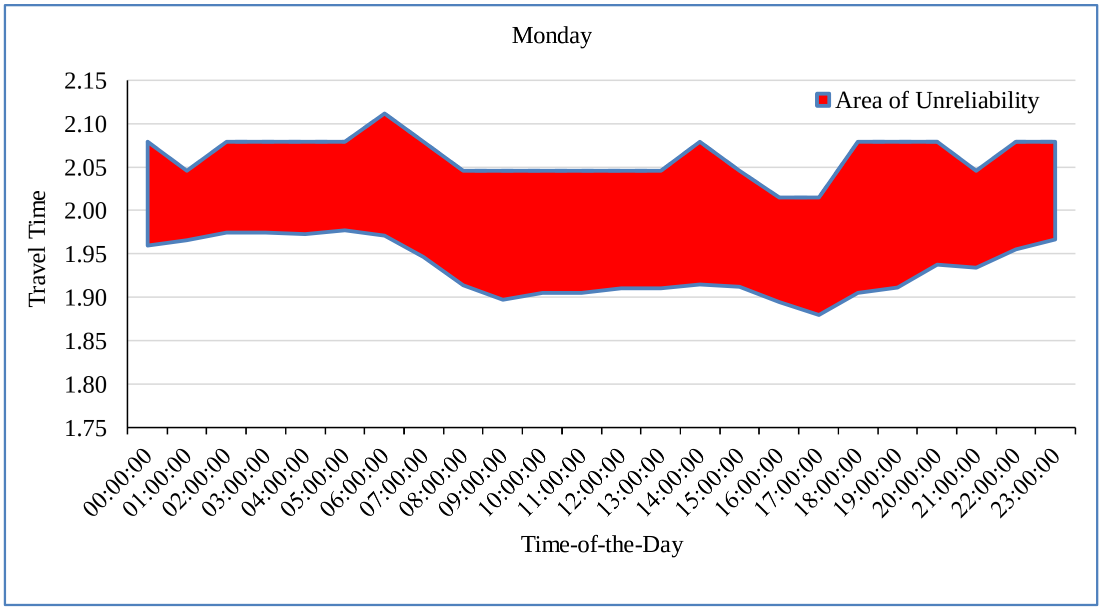


Figure 18. Area between Average and 95th Percentile Travel Time

8.2. Value of Buffer Time (BT)

As discussed in the previous chapters, reliability accounts for consistency in travel times. Travelers account for the variability in the travel time and plan for buffer time along with the average travel time to their destination. The unreliability increases as the buffer time increases. The cost associated with the planned buffer time varies when compared to the travel time savings. For example, a traveler may plan for a buffer time of 15 minutes to his/her 25-minute trip. The planned additional 15 minutes is because of the uncertainty in the travel time between the origin and destination. As the uncertainty in the travel times on the road links between the origin and destination decreases, the buffer time planned will also decrease. The value of the planned buffer time is different when compared to the travel time savings on the 25-minute trip. It also varies by time-of-the-day and day-of-the-week. The following example illustrates the use of value of reliability in estimating benefits.

Example: Estimating the Benefits from a Reliable Route

Consider a 10-mile road link with average travel times as presented in Column 2 of Table 36. Column 3 is buffer time for each trip during the given hour. Similarly, the traffic volumes on the given road for each hour between 07:00 AM to 10:00 PM are shown in Column 4. Column 5 shows the total passengers traveled with 1.2 as the average vehicle occupancy rate. Column 6 shows the value of travel time, while Column 7 shows the value of buffer time. For this project or alternative, the total value of travel time is $273,428,289 per year, while the total value of buffer time is $67,743,270 per year.

Like the above example, a real-world scenario is considered to illustrate the value of reliability. For this purpose, road widening of 10.3-mile section from 4-lane to 6-lane on I-40 South of Trinity Road, Raleigh is considered. After road widening, the difference between the maximum travel time and the average travel time decreased from 9 minutes to 2 minutes during the morning peak hour. Similarly, the difference between the maximum travel time and the average travel time decreased from 10.5 minutes to 2.7 minutes during the evening peak hour.

The generalized value of buffer time is $0.45 per minute. The traffic volumes after completion of road widening are considered to evaluate the value of improved reliability from road widening. Table 37 shows the overall value of the project due to improved reliability during peak hours upon widening the I-40 section. A quick comparison with benefits due to decrease in travel time for the same section indicates greater benefits achieved due to reduction in buffer time along this study section.

Table 36. Estimation of Cost Benefits from Reliable Route by Time of Day

Time-of-the-day	Average Travel Time	Buffer Time	Traffic Volume	Total Passengers	Value of Travel Time per Year	Value of Buffer Time per Year
07:00 AM to 08:00 AM	25	10	4,000	4,800	22,338,000	$7,884,000
08:00 AM to 09:00 AM	26	9	4,200	5,040	24,393,096	$7,450,380
09:00 AM to 10:00 AM	23	10	3,800	4,560	19,523,412	$7,489,800
10:00 AM to 11:00 AM	22	3	3,500	4,200	17,200,260	$2,069,550
11:00 AM to 12:00 PM	21	4	3,400	4,080	15,949,332	$2,680,560
12:00 PM to 01:00 PM	20	3	3,200	3,840	14,296,320	$1,892,160
01:00 PM to 02:00 PM	20	3	3,000	3,600	13,402,800	$1,773,900
02:00 PM to 03:00 PM	20	3	2,600	3,120	11,615,760	$1,537,380
03:00 PM to 04:00 PM	21	3	3,200	3,840	15,011,136	$1,892,160
04:00 PM to 05:00 PM	23	5	3,700	4,440	19,009,638	$3,646,350
05:00 PM to 06:00 PM	26	10	4,400	5,280	25,554,672	$8,672,400
06:00 PM to 07:00 PM	27	10	4,200	5,040	25,331,292	$8,278,200
07:00 PM to 08:00 PM	24	9	3,900	4,680	20,908,368	$6,918,210
08:00 PM to 09:00 PM	23	6	3,450	4,140	17,725,203	$4,079,970
09:00 PM to 10:00 PM	20	3	2,500	3,000	11,169,000	$1,478,250
Total					**$273,428,289**	**$67,743,270**

Table 37. Cost Benefits of Improved Reliability from Road Widening of I-40

Road Widening from 4-Lane to 6-Lane - (I-40) South of Trinity Road						
Time-of-the-day	**Traffic Volumes**		**Buffer Time**		**Reduction in Buffer Time (Minutes)**	**Value of Reliability**
	Before	**After**	**Before**	**After**		
*AM Peak	6700	6400	9.0	2.0	7.0	$20,160
*PM Peak	6800	7000	10.5	2.7	7.8	$24,570

* AM peak values are for Westbound and PM Peak Values are for Eastbound.

Chapter 9. Conclusions

This research report presents a review on reliability performance measures, selection of reliability performance measures for analysis, gathering perceptions of North Carolina road users on reliability, analysis of data collection and the value of travel time measures and reliability to evaluate the impact of transportation alternatives. The average travel time is correlated to most travel time and travel time percentile based measures. It can be used to assess travel time savings – before-after comparison or selection between projects. Buffer time and buffer time index are correlated to most travel time reliability indices and variance based measures. They can be used for ranking, prioritization and allocation of resources. In addition, buffer time indicates the planned additional trip time and road user's general perception of transportation system reliability. Therefore, average travel time and buffer time are recommended for evaluating the impact of transportation projects / alternatives. The combination of average travel time and buffer time is important for assessing reliability of a route from motorists' perspective. Quantifying and using these measures to assess the impact of transportation projects / alternatives eases further with advancements in technology and availability of rich travel time datasets.

A preliminary random general survey was followed by focus group survey and final random survey to evaluate motorists' perception towards reliability. The preliminary random general survey consisted of questions which were aimed to capture stated preference choices on evaluating how the participants would react to the hypothetical situations. Based on the results from preliminary random general survey of 417 participants, the average travel time for daily commute in the state of North Carolina is 23.47 minutes. The average additional trip time (planned maximum buffer time) is equal to 10.54 minutes. It does not seem to vary based on the average travel time. Some differences were observed when evaluated based on income level of the participant. Low income group participants followed by high income group participants tend to plan for higher additional trip time than medium income participants. Males tend to choose an unreliable route more than females. This indicates a difference in risk attitude by gender.

The generalized value of travel time for North Carolina is estimated equal to \$0.51 per minute. While the generalized value of additional trip time is also \$0.51, participants are willing to pay, on average, \$0.11 to reduce travel time by one minute. The value of additional trip time was observed to be different for peak hours and off-peak hours. It was also observed to vary by gender and income group of the participant. The computed value of additional trip time can be used as the maximum value of buffer time to evaluate the benefits from any proposed / designed transportation alternatives.

Nine focus group meetings were conducted across North Carolina to collect data from 93 participants as a part of this research. The participants of the focus group survey were asked to choose between a reliable route and unreliable route. The focus group survey aimed to observe participants' trade-off between travel time savings and reliability. Results from focus group survey indicate that higher percent of participants are willing to opt for routes with lower number of days of unreliability as they would be having some travel time savings. However, as the unreliability increases (number of days), participants started shifting from an unreliable route to a reliable route. The generalized value of buffer time for North Carolina based on focus group survey is estimated as $0.48 per minute. However, the focus group sample did not seem to be a good representation of North Carolina population. Therefore, this was followed by the final random survey.

The final random survey comprised 357 participants who were asked to choose between two routes, a reliable route with longer travel time and an unreliable route with shorter travel time (as in the case of focus group survey). The maximum tolerance limit for unreliability is observed to be 4 days a month for a maximum buffer time of 20 minutes for a typical work day trip (~23 minutes).

Differences were observed when the findings from the final random survey were compared to the focus group survey. The generalized value of buffer time for North Carolina based on the final random survey is estimated as equal to $0.45 per minute. This is based on the maximum buffer time that participants were willing to accept by selecting an unreliable route, hoping to save travel time for most of the trips, before choosing a reliable route. This value is less than the value of additional trip time from the preliminary random general survey and the value of buffer time from the focus group survey. It is recommended for use to evaluate the impact of transportation alternatives, in addition to the generalized value of travel time. Table 38 shows the recommended value of travel time, value of travel time savings, value of willingness to pay and value of buffer time computed from this research.

Table 38. Recommended Values to Assess Transportation Alternatives

Variable	Value ($/hour)
Value of Travel Time & Value of Travel Time Savings	30.60
Value of Willingness to Pay	6.60
Value of Buffer Time	28.80

9.1. Implementation Plan

Based on the findings from this research, it is recommended that NCDOT use the average travel time and buffer time (difference between the 95th percentile travel time and the average travel time) as performance measures for evaluation of transportation projects and alternatives. This data could be easily extracted hourly from sources such as HERE and INRIX.

The recommended monetary values for average travel time and buffer time are $0.51 and $0.45, respectively. It is suggested that the monetary values be used for upcoming assessments and compare them with existing practices (say, based on travel time and/or delay or volume-to-capacity ratio) in North Carolina prior to large-scale implementation.

9.2. Limitations of Current Research and Scope for Future Work

The outcomes from this research to monetize reliability for evaluating the impact of transportation alternatives is completely based on the surveys obtained from passenger car users. The outcomes from this research are only applicable for evaluating value of travel time reliability for passenger cars. The findings are not applicable for other modes of travel (example, trucks). Unreliable travel times for truckers could lead to late shipments and disruption of on-time delivery, resulting in loss of competitive edge on other shippers. Therefore, the value of travel time reliability for trucks could be very high compared to passenger car travel time reliability. Effective methods on evaluating travel time reliability for freight and monetizing reliability for trucks (freight transportation) warrants an investigation.

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