January 2012

Modeling Travel Time and Reliability on Urban Arterials for Recurrent Conditions

Prony Bonnaire Fils
University of South Florida, pbonnair@mail.usf.edu

Scholar Commons Citation
Bonnaire Fils, Prony, "Modeling Travel Time and Reliability on Urban Arterials for Recurrent Conditions" (2012). *Graduate Theses and Dissertations.*
http://scholarcommons.usf.edu/etd/3984

Modeling Travel Time and Reliability on Urban Arterials for Recurrent Conditions

by

Prony Bonnaire Fils

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

Co-Major Professor: Jian John Lu, Ph.D.
Co-Major Professor: Pei-Sung Lin, Ph.D.
Rebecca Wooten, Ph.D.
Abdul Pinjari, Ph.D.
Yu Zhang, Ph.D.
Kingsley Reeves, Ph.D.

Date of Approval:
April 30, 2012

Keywords: Multiple Linear Regression, Correlation,
Buffer Time, Influencing Factors, Transportation Planning

Dedication

This dissertation is dedicated to my wonderful wife Fhadia, my lovely kids Prudny and Nyrdia, my dedicated parents Leonie and Victor with appreciation for the support, help, prayer, and encouragement that I have received during the years that I have devoted for the doctorate degree.

Acknowledgements

I express my thanks and gratitude to my co-major professors Dr. Pei Sung Lin and Dr. John Lu for their guidance and support on this dissertation. They were very patient spending a lot of time over the past four years to supervise my study, discuss research issues, offer insights and suggestions, and invaluable input. Special thanks also to my other committee members for their advice and their input. First of all, I thank Dr. Rebecca Wooten who analyzed the statistical and mathematical data from the single linear regression to the multiple regression analysis. My thanks to Dr. Yu Zhang for her comments, criticism, and help to improve the model framework and the travel time reliability threshold. Similarly, cheers and thanks to Dr. Abdul Pinjari who commented on the selected factors included in the model and provided advice to improve the literature review and the model. I also thank Dr. Kingsley Reeves who expressed at the proposal defense the inclusion of the signal timing in the selected factors. Furthermore, I owe a big word of thanks to Sensys Networks to let me access their travel time database through the ATTS (Arterial Travel Time System). My thanks also to Sarasota County Traffic Operations Division that provided the traffic data needed for the model validation and robustness. Thank you to the many others, too many to name, who have played some role in making this doctoral research effort possible.

Finally, many thanks, hugs, and kisses go out to my wonderful wife Fhadia, my lovely kids Prudny and Nyrdia who supported and tolerated me in the last four years and enabled me to reach this milestone in my life.

Table of Contents

List of Tables

List of Figures

Abstract

Travel time reliability is defined as the consistency or dependability in travel times during a specified period of time under stated conditions, and it can be used for evaluating the performance of traffic networks based on LOS (Level of Service) of the HCM (Highway Capacity Manual). Travel time reliability is also one of the most understood measures for road users to perceive the current traffic conditions, and help them make smart decisions on route choices, and hence avoid unnecessary delays (Liu & Ma, 2009). Therefore, travel time reliability on urban arterials has become a major concern for daily commuters, business owners, urban transportation planners, traffic engineers, MPO (Metropolitan Planning Organization) members as congestion has grown substantially over the past thirty (30) years in urban areas of every size.

Many studies have been conducted in the past on travel time reliability without a full analysis or explanation of the fundamental traffic and geometric components of the corridors. However, a generalized model which captures the different factors that influence travel time reliability such as posted speed, access density, arterial length, traffic conditions, signalized intersection spacing, roadway and intersection geometrics, and signal control settings is still lacking. Specially, there is a need that these factors be weighted according to their impacts.

This dissertation by using a linear regression model has identified 10 factors that influence travel time reliability on urban arterials. The reliability is measured in term of

travel time threshold, which represents the addition of the extra time (buffer or cushion time) to average travel time when most travelers are planning trips to ensure on-time arrival. “Reliable” segments are those on which travel time threshold is equal to or lowers than the sum of buffer time and average travel time.

After validation many scenarios are developed to evaluate the influencing factors and determine appropriate travel times reliability. The linear regression model will help 1) evaluate strategies and tactics to satisfy the travel time reliability requirements of users of the roadway network—those engaged in person transport in urban areas 2) monitor the performance of road network 3) evaluate future options 4) provide guidance on transportation planning, roadway design, traffic design, and traffic operations features.

Chapter 1- Introduction

1.1 Context

Travel time is one of the most important measurements for evaluating the operating efficiency of traffic networks and accurate and reliable travel time information has become increasingly important for traffic engineers, daily commuters, residents, business owners, MPO members etc. Chen et al. (2003) stated that travel time reliability is “an important measure of service quality for travelers”. Personal and business travelers value reliability because it allows them to make better use of their own time. Shippers and freight carriers require predictable travel times to remain competitive. Reliability is also a valuable service that can be provided on privately-financed or privately operated highways.[1] Nam et al. (2006) argued that travelers’ tastes for travel time and travel time reliability vary across times of day and that route choice is based on a combination of travel time, travel time reliability, and cost.

However, the travel time experienced by a traveler making a trip on an arterial segment is not just the result of his or her own travel choices (destination, mode, route, speed), but also the choices of many other travelers, not necessarily only those traveling the same segment. Moreover, a substantial component of driver behavior may not be classified as rational choice behavior, but rather a product of the different characteristics of individual drivers; for example attention level, driving style, risk assessment, and their

---

[1] FHWA. Travel Time Reliability: Making it There on Time, All the Time, 2006.

vehicles, such as acceleration and deceleration capabilities (Van Lint, J.,2004). Finally, travel time reliability on an arterial segment is also determined by processes completely beyond the control of individual or groups of drivers or even the organization responsible for the road facility such as weather, calamities, incidents and accidents, traffic patterns, seasonal patterns and so on. Therefore, the travel time reliability on arterial networks is usually not only a function of traffic flow, driver behavior, traffic composition, link capacity and speed limit, but also involves numerous other factors such as signal timing, roadway and intersection geometries, adjacent land use and development, median type, signalized intersection spacing, and conflicting traffic from cross streets.

It is almost impossible to predict the traffic-influencing events (traffic incidents, weather, and work zones), behaviors (both rational and irrational) of all individual drivers in a road network, and all external circumstances that may affect travel time reliability. In this dissertation, the linear regression model seeks to deduce the general relationships among factors that influence travel time reliability on urban arterials. Many studies have been conducted in the past on travel time reliability, but most are focused on freeways and non-recurrent factors on arterials. Conversely, the impact of recurrent factors on travel time reliability on urban arterials is still a very complex and challenging problem.

1.2 Background and Problem Statement

1.2.1 Urban Arterials and Travel Time Reliability

Arterial roads, or arterial thoroughfares, are high-capacity urban roads whose primary function is to deliver traffic from collector roads to freeways, and between major activity centers of a metropolitan area at the highest level of service possible. As such, many arteries are limited-access roads, or feature restrictions on private access. They normally are divided into two classes, major (principal) and minor, and their design ranging from four to eight through lanes is very challenging to transportation professionals working in the design field. As described by ITE (Institute of Transportation Engineers):

> ….Urban arterials streets often present the most challenging type of geometric design because of the need to provide safe and efficient operations for multiple types of users under unusual and constrained conditions. In addition, the designer must be prepared to apply criteria for differing types of arterial design features to address transitions as an arterial moves through varying types and densities of land uses that often exist along arterial corridors in urban settings (Institute of Transportation Engineers, Urban Street Geometric Design Handbook, 2008. p.7).

Urban arterials are the main thoroughfares on which U.S. motorists do most of their driving. According to HCM 2000 urban arterials are signalized streets that primarily serve through-traffic and that secondarily provide access to abutting properties, with signal spacing of 2.0 mi or less.[2] Today, U.S. motorists travel almost 80 percent more mile on urban arterials compared with rural arterials and most of urban arterials were not originally designed to accommodate today's heavy traffic.[3] Instead, they have evolved as urban and suburban traffic has increased. Consequently, congestion has not only grown substantially over the past 30 years in cities of every size, it has become more volatile as well.[4] According to Texas Transportation Institute‘s researchers, congestion levels in 85

---

[2] Highway Capacity Manual (HCM) 2000.

[3] Insurance Institute for Highway Safety" Traffic Engineering Approaches to Reduce Crashes on Urban Arterial Roads", April 2000.

[4] Texas Transportation Institute, 2011 Annual Urban Mobility Report.

of the largest metropolitan areas have grown in almost every year in all population group from 1982 to 2010.[5] In 2010, the amount of average delay endured by the average commuter was 34 hours, up from 14 hours in 1982. The cost of congestion is more than $ 100 billion, nearly $750 for every commuter according to the 2010 Annual Urban Mobility Report.

This trend is expected to continue as America becomes increasingly urbanized, 85 percent by 2020.[6] The increasing congestion levels have influenced travel time reliability, which is significant to all the transportation system users whether they are vehicle drivers, transit riders, freight shippers, or even air travelers. Moreover, travel times are so unreliable on U.S. highways that travelers must plan for these problems by leaving early just to avoid being late. This means extra time out of everyone's day that must be devoted to travel; even if it means getting somewhere early, that is still time travelers could be using for other endeavors. The urban arterial network is so unreliable commuters could be late for work or after-work appointments, business travelers could be late for meetings, and truckers could incur extra charges by not delivering their goods on time.

There is considerable evidence from stated preference survey results related to demand estimation for toll roads and public transport projects that traveler’s willingness to pay, extends to reliability of travel time, especially for time-sensitive trips.[7] The willingness to pay for reductions in the day-to-day variability of travel time is referred to as VOR (value of reliability). Some U.S studies have found that users place a value on travel time variability of more than twice the value placed on the average travel time.[8] In

---

[5] Texas Transportation Institute, 2011 Annual Urban Mobility Report.
[6] Human Development Reports.
[7] Monitoring and Modeling Travel Time Reliability, Transport Futures, Feb. 2008
[8] Ibid

addition, traffic professionals recognize the importance of travel time reliability because it better quantifies the benefits of traffic management and operation activities than simple averages.

In addition to having a value to users, in terms of travel time certainty and travel time reductions due to reduced in average trip times, reliability has an indirect impact on trip costs, by potentially reducing fuel consumption, vehicle emissions and public transport operating costs.[9]

Therefore determining the different factors that influence travel time reliability on urban arterials is significant. Road agencies and authorities have an interest and responsibility to address the factors that cause unreliable travel time. The reliability measure should provide information about the amount of time that should be budgeted for a trip. The calculation process for any specific measure formulation should control for variations that are not relevant to the trip planning decision, although these elements will vary. This may include factors such as day-to-day and time variations (because travel decisions may be made with knowledge of the day and time) and variation in road characteristics (because travelers typically examine their trip travel time rather than each road section separately) (Lomax et al., 2003).

1.2.2 Travel Time Reliability and Road Users in the Coming Years

The FHWA (Federal Highway Administration) projects that between 1998 and 2020 domestic freight volumes will grow by more than 65 percent, increasing from 13.5 billion tons to 22.5 billion tons.[10] FHWA expects trucks to move over 75 percent more

---

[9] Texas Transportation Institute, 2011 Annual Urban Mobility Report.

[10] Monitoring and Modeling Travel Time Reliability, Transport Futures, Feb. 2008

tons in 2020, capturing a somewhat larger share of total freight tonnage than currently. This rapid growth in truck volume can be attributed to a number of factors including the shift of significant freight activity from rail and other modes to truck, and the changes in the economy and business practices such as just-in-time deliveries of inventory items that increase delivery frequencies (Polzin, S., 2006). To carry this freight, truck VMT (Vehicle Mile Travelled) is expected to grow at a rate of more than three percent annually over the same period (DRI-WEFA, 2000).

E-business is expected to increase significantly over the next decades and will influence the land use patterns and VMT. The shopping from home (via catalogs, cable television shows, and the internet) and highly efficient package delivery companies, such as Federal Express and United Parcel Service, will increase trips from local businesses to homes. It will also drive freight supply and demand away from long-haul carriers toward less-than-truck load or smaller truck freight shipments as a significant portion of all types of retailing required next-day delivery, same-day delivery, and just-in-time delivery.

The demographic shifts likely to occur between 2000 and 2020 in the U.S. population will also generate more traffic on urban roadways and increase congestion. The U.S. Census Bureau projects the U.S. population will be somewhat better off economically, older, better educated, households will be smaller and household vehicle ownership to increase.[11] In the coming years, the number of older drivers on the road is expected to at least double. This increase is attributable to both the overall increase in the older population, as well as the anticipated trend for older women to drive in greater proportions than their previous cohorts (Pisarski, A., 2006). These household

---

[11] U.S. Census Bureau, U.S. Population Projection by Age, Sex

composition shifts, changes in labor force participation and household income, and shifts in licensing and vehicle ownership all will affect transportation and individual mobility, which is expected to increase the highway VMT by 60 percent in 2020[12](3,881 billion compared with 2.631 billion in 2000).

At the same time, researchers and practitioners are aware of the impacts of travel time reliability and consequently have adjusted their methodologies. For instance, in transportation planning, incorporating the value of travel time reliability has been found to significantly enhance mode choice models (Pinjari & Bhat, 2006; Liu et al., 2007). The second Strategic Highway Research Program (SHRP2) determines reliability as one of the four transportation factors that needs to be addressed when making a highway capacity expansion decision.[13] Additionally, reliability research is developing the means for state DOTs and Metropolitan Planning Organizations to fully integrate mobility and reliability performance measures and strategies into the transportation planning processes. Studies are under way to include reliability factors into the Highway Capacity Manual. A guide on roadway design features will be written to support the reduction of delays that reduce travel time reliability so that such features can be considered for inclusion in the AASHTO Policy on Geometric Design of Highways and Streets.[14]

Reliability requirements for personal trips vary considerably depending on trip type (commuter trips, medical appointments, school trips, attending places of worship, day-care pickup, and social/recreational), time of day (peak period versus off-peak) and the travel setting and conditions. Reliability requirements vary depending on the portion

---

[12] U.S Department of Energy/Energy Information Administration

[13] Cambridge Systematics, Inc., High Street Consulting Group, TransTech Management, Inc., Spy Pond Parterners, Ross & Associates. Performance Measure Framework for Highway Capacity Decision Making. Washington, D.C.: Transportation Research Board of National Academies, 2009. NCHRP Report 618

[14] Transportation Research Board, Updating Reliability Research in SHRP 2, January 2011

of the road network used, geographic areas (urban or rural), and the factors that contribute to the uncertainty of arrival time on these arterials, such as rail road crossing, number of signalized intersections, signal timing cycle length, posted speed, roadway characteristics, school bus stops.

Reliability requirements for business trips (freight carriers, shippers, truckers) vary also depending on the situation and business characteristics (small businesses, family owned businesses). Transportation agencies must understand these different user requirements if they expect to meet them effectively. As pointed out by TRB (Transportation Research Board).

> ….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 (Transportation Research Board, in SHRP 2 L11, Evaluating Alternative Operations Strategies to Improve Travel Time Reliability, 2010).

1.3 Research Objectives

The dissertation will address travel time reliability on major urban arterials. We adhere to the definition for arterials given in the Highway Capacity Manual 2000:

“Arterials are signalized streets that primarily serve through-traffic and that secondarily provide access to abutting properties, with signal spacing of 2.0 mi or less”. Travel time the time it takes a typical commuter to move from the beginning to the end of a corridor (Florida Department of Transportation, 2000) and travel time reliability is defined as the consistency or dependability in travel times during a specific period of time under stated conditions. This consistency has to consider the travel time threshold due to the impact of the influencing factors.

The reliability is measured in term of travel time threshold, which typically represents the addition of the extra time (or cushion time) to the average travel time when most travelers are planning trips to ensure on-time arrival. “Reliable” segments are those on which travel time threshold is equal to or lowers than the buffer time added to the average travel time.

Reliability is concerned with three key elements of this definition:

- First, reliability is a probability which is concerned with meeting the specific probability of consistency or dependability at a statistical confidence level.
- Second, reliability applies to a defined threshold and specific time periods.
- Third, reliability is restricted to operation under stated conditions. This constraint is necessary because it is impossible to design a system for unlimited conditions.

The main objective of this dissertation is to develop a travel time reliability model that is adaptive, general, robust, and accurate to identify the linear relationship between the continuous dependent variable (travel time reliability) and other independent variables (the different factors that influence travel time reliability) on urban arterials.

1.3.1 Adaptability of Model

"Traffic processes are characterized by constant change, due to structural changes in both traffic demand patterns as well as traffic supply characteristics. The model should be able to track these changes and adapt accordingly to preserve its validity" (Van Lint, J. W.C., 2004).

1.3.2 Generality of Model

The model will be general, and not-location-specific, at least in terms of mathematical structure and the overall input-output relationships. For example, an urban arterial model should be applicable on different arterial networks, with different geometrical properties (number of lanes, access density). A model that requires specific design for every location is not likely to be successfully deployed on a large scale.

1.3.3 Robustness of Model

If the data to the model is corrupt, which is a common problem in real-time traffic data collection systems, the model should be able to produce reasonable outcomes (which could even be a message indicating something is wrong).

1.3.4 Accuracy of Model

The difference between what actually happened and the information (in the case of travel time) should be as small as possible, which is subject to location and application specific circumstances. Roughly, model output errors can be categorized into two types:

structural errors (bias) and random errors (variance). Put simply, an accurate model makes small (quantitative mistakes), in terms of both bias and variance.

This travel time reliability model will be useful to:

- evaluate strategies and tactics to satisfy the travel time reliability requirements of users of the urban roadway networks,
- monitor the performance of road networks,
- evaluate future roadway improvement options,
- provide guidance on planning, geometric and traffic designing, and traffic operations features.

1.4 Dissertation Outline

Chapter 1 explained the importance of travel time reliability measurements for technical and non-technical audiences. After the definition of urban arterials from HCM, this chapter outlined the increasing impacts of U.S motorists traveling on these arterials (congestion has grown and become more volatile). The importance of travel time reliability for road users in the coming years is also described. The research objectives, which describe a new travel time threshold (reliability) based on the buffer index, the buffer time, and the average travel time, are included in this chapter. In addition, the theoretical and practical relevance of the model are illustrated.

Chapter 2 is the literature review where previous studies on travel time reliability and previous travel time reliability calculation methods are described. The advantages and disadvantages of these studies and calculation methods are also analyzed.

Chapter 3 is the methodology where the statistical analysis (single and multiple linear regressions), the selected influencing factors, and model framework are explained in details.

In chapter 4, the data collection architecture (geographic areas, time elements), the data collection methods (comparison between the selected data collection method and other alternative methods) are analyzed.

Chapter 5 is the statistical results of the data and discussion. The travel time reliability threshold for each segment, the buffer index and buffer time for each segment, the correlation among contributing factors, the model linear regression equation, model validation, model generality and robustness, scenarios analysis, guidance on roadway design, traffic design are part of this chapter.

Finally, in chapter 6 the limitations and the main contributions of this dissertation to the state-of-the-art are presented and guidelines for future research are outlined.

This dissertation is concluded with Appendix A (Travel Times for the Segments Driving Westward), Appendix B (Travel Times for the Segments Driving Eastward), Appendix C (List of Acronyms), and Appendix D (Third Party Permission).

Chapter 2-Literature Review

2.1 Previous Studies on Travel Time Reliability

Although research on travel time reliability for freeways is very rich, research on arterial travel time reliability is quite limited. Prediction of travel time is potentially more challenging for arterials than for freeways because vehicles traveling on arterials are subject not only to queuing delay but also to signal delays as well as delays caused by vehicles from the cross streets (Yang, J., 2006).

Abishai Polus (1979) in "A study of Travel Time and Reliability on Arterial Routes" analyzed travel time and operational reliability on arterial routes. Reliability is viewed in terms of the consistency of operation of the route under investigation and defined in terms of the inverse of the standard deviation of the travel time distribution. Under certain assumptions, travel time behavior on an arterial route is seen to closely follow a gamma distribution; the reliability measure can be derived accordingly. Utilizing arterial travel time data from the Chicago area, both a regression and a statistical model are shown to serve as efficient techniques in predicting reliability. The prediction models are evaluated.

Fu et al. (2001) in "An Adaptive Model for Real-Time Estimation of Overflow Queues on Congested Arterials "presented a model that can be used to estimate one of the congestion measures, namely real-time overflow queue at signalized arterial approaches. The model is developed on the basis of flow conservation, assuming that time-varying traffic arterials can be obtained from loop detectors located at signalized approaches and signal control information is available online. A conventional microscopic simulation model is used to generate data for evaluation of the proposed model. A variety of scenarios representing variation in traffic control, level of traffic congestion and data availability are simulated and analyzed.

The “Modeling Network Travel Time Reliability under Stochastic Demand” study conducted by Stephen Clark and David Watling in 2003 proposed a method for estimating the probability distribution of total network travel time in the light of normal day-to-day variations in the travel demand matrix over a road traffic network. A solution method is proposed, based on a single run of a standard traffic assignment model, which operates in two stages. In stage one, moments of the travel time distribution are computed by an analytic method, based on the multivariate moments of the link flow vector. In stage two, a flexible family of density functions is fitted to these moments. Stephen Clark and David Watling discussed how the resulting distribution may in practice be used to characterize unreliability. Illustrative numerical tests are reported on a simple network, where the method is seen to provide a means of identifying sensitive or vulnerable links and for the examining the impact on network reliability of changes to link capacities.

Van Zuylen, H. J. et al. (2005) stated that traffic operations on weaving sections are characterized by intense lane changing maneuvers and complex vehicle interactions, which can lead to certain variations in travel time. One of the factors affecting the travel time variability of weaving sections is the length of the weaving section. In “Travel Time Variability of Freeways Weaving Sections Control in Transportation Systems”, the relation between weaving section length and travel time variability is investigated. This is done based on both a simulation approach and on empirical data. Both indicate a relationship between a certain weaving section length threshold and travel time variability increases. These implications of this (preliminary) result are discussed for geometric design purposes and for possible control applications, which can reduce the travel time variability in the short weaving sections.

Van Lint J.W. et al. (2005) in "Monitoring and Predicting Freeway Travel Time Reliability: Using Width and Skew of Day-to-Day Travel Time Distribution" proposed many different aspects of the day-to-day travel time distribution as indicators of reliability. Mean and variance do not provide much insight because those metrics tend to obscure important aspects of the distribution under specific circumstances. It is argued that both skew and width of this distribution are relevant indicators for unreliability; therefore, two reliability metrics are proposed. These metrics are based on three characteristic percentiles: the 10th, 50th, and 90th percentiles for a given route and TOD-DOW (Time of Day-Day of Week) period. High values of either metric indicate high travel time unreliability. However, the weight of each metric on travel time reliability may be application or context specific. The practical value of these particular metrics is that they can be used to construct so-called reliability maps, which not only visualize the unreliability of travel times for a given DOW-TOD period but also help identify DOW-TOD periods in which congestion will likely set in (or dissolve). That means identification of the uncertainty of start, end, and, hence, length of morning and afternoon peak hours. Combined with a long-term travel time prediction model, the metrics can be used to predict travel time (un)reliability. Finally, the metrics may be used in discrete choice models as explanatory variables for driver uncertainty.

Nam Doohee et al. (2005) in “Estimation of Value of Travel Time Reliability” expressed reliability in terms of standard deviation and maximum delay that was measured based on triangular distribution. In order to estimate value of time and value of reliability, the multinomial and Nested Logit models were used. The analysis results revealed that reliability is an important factor affecting mode choice decisions. Since values of reliability were higher than values of time, the policy to increase travel time reliability gained more benefit than to reduce the travel time at the same level of improvement.

Al-Deek et al. (2006) in “Using Real-Life Dual-Loop Detector Data to Develop New Methodology for Estimating Freeway Travel Time Reliability**”** stated that travel time reliability captures the variability experienced by individual travelers, and it is an indicator of the operational consistency of a facility over an extended period. A roadway segment is considered 100% reliable if its travel time is less than or equal to the travel time at the posted speed limit. Weekends had a different peak period, so this study focuses on weekdays. The freeway corridor is a collection of links arranged and designed to achieve desired functions with acceptable performance and reliability. The relationship between the freeway corridor system reliability and the reliability of its links is often misunderstood. For example, the following statement is false: “If all of the links in a system have 95% reliability at a given time, then the reliability of the system is 95% for that time.”

In 2006, Jiann-Shiou Yang in a research project entitled “A Nonlinear State Space Approach to Arterial Travel Time Prediction” focused on the modeling and the prediction of arterial section travel times via the time series analysis and Kalman recursions techniques. The ARIMA (Autoregressive Integrated Moving Average) model and properties are introduced and its state-space representation is also derived. The developed state-space model is then further used in the Kalman filter formulation to perform one-state-ahead Travel Time Prediction. The performance is conducted on a section of Minnesota State Highway 194, one of the most heavily congested corridors in the area. During the modeling process, Jiann-Shiou Yang used the information criteria to select model orders, while the model parameter values were estimated via the Hannan-Rissanen algorithm. The models developed were further validated via both the residual analysis and portmanteau test. The project found, in general, the ARIMA time series models produce reasonably good prediction results for most of the road sections studied. The project also demonstrated the potential and effectiveness of using the time series modeling in the prediction of arterial travel time.

In 2007, the Transportation Research Center at University of Florida has conducted various research sponsored by FDOT (Florida Department of Transportation) for freeways and arterials in Florida.[15] Using four factors (congestion, work zones, weather, and incidents) that may affect travel time, models for estimating the travel time reliability on freeway facilities were developed. Furthermore, three parts of travel time (travel time in motion, waiting time in queue, and moving time in queue) were estimated separately and then combined together to estimate travel time on arterials.

Sumalee and Watling (2007) proposed the efficient partition-based method to evaluate the transport network from the view point of travel time reliability after the disasters. The algorithm will dissect and classify the network states into reliable,

---

[15] Transportation Research Center, University of Florida, “Travel Time Reliability Models for Freeways and Arterials.” 2007

unreliable, and un-determined partitions. By postulating the monotone property of the reliability function, each reliable and/or unreliable state can be used to determine a number of other reliable and/or unreliable states without evaluating all of them with an equilibrium assignment procedure. It also proposes the cause-based failure framework for representing dependent link degradation probabilities. The algorithm and framework proposed are tested with a medium size test network to illustrate the performance of the algorithm.

Shao et al. (2007) proposed a travel time reliability-based traffic assignment model to investigate the rain effects on risk-taking behaviors of different road users in networks with day-to-day demand fluctuations and variations in travel time. In view of the rain effects, road users' perception errors on travel time and risk-taking behavior on path choices are incorporated in the proposed model with the use of a Logit-based stochastic user equilibrium framework. A numerical example is illustrated for assessment of the rain effects on road networks with uncertainty.

Lyman and Bertini (2008) in “Using Travel Time Reliability Measures to Improve Regional Transportation Planning and Operations” examined the use of measured travel time reliability indices for improving real-time transportation management and traveler using archived ITS (Intelligence Transportation System) data. Beginning with a literature review of travel time reliability and its value as a congestion measure, Lyman and Bertini described twenty regional transportation plans from across the nation. Then, a case study using data from Portland, Oregon, several reliability measures are tested including travel time, 95th percentile travel time, travel time index, buffer index, planning time index, and congestion frequency. The buffer index is used to prioritize freeway corridors according to travel time reliability. They concluded that MPO should use travel time reliability in the following ways: 1) incorporate it as a system-wide goal; 2) evaluate roadway segments according to travel time reliability measures; and 3) prioritize the capacity expansion of roadway segments using these measures.

Tu Huizhao et al. (2008) in “Travel Time Reliability Model on Freeways” clarified the attributes of reliability and proposed a new analytical formula to express travel time unreliability in terms of these elements, in which the travel time (un)reliability is computed as the sum over the products of the consequences (variability or uncertainty) and corresponding probabilities of traffic breakdown (instability). The travel time reliability model is considered as a function of a variety of factors. In essence, these factors are conditionals, that is, the function expresses travel time reliability for a certain inflow level, given certain circumstances. These circumstances include road characteristics and all other relevant factors like traffic control measures, the prevailing traffic state (congested or not), and possibly external factors such as weather and luminance. The model is validated and calibrated on the basis of the empirical data collected from Regiolab-Delft traffic monitoring system. The researchers found that both the probability of traffic breakdown and travel time unreliability increase with the increasing inflows.

Pu Wenjing (2010) in “Analytic Relationships between Travel Time Reliability Measures” analyzed the measures used in transportation engineering including the 90th or 95th percentile travel time, standard deviation, coefficient of variation, buffer index, planning time index, travel time index, skew statistic, misery index, frequency of congestion, on-time arrival, and others. The paper analytically examined a number of reliability measures and explored their mathematical relationships and interdependencies. With the assumption of lognormal distributed travel times and the use of percent point function, a subset of reliability measures is expressed in terms of the shape parameter and/or the scale parameter of the lognormal distribution (Figure 1). This enables a clear understanding of the quantitative relationships and variation tendencies of different measures. Contrary to some previous studies and recommendations, the paper demonstrated that coefficient of variation, instead of a standard deviation, is a very good proxy for several other reliability measures. The use of average-based buffer index or average-based failure rate is not always appropriate, especially when travel time distributions are heavily skewed (in which case median-based buffer index or failure rate is recommended).

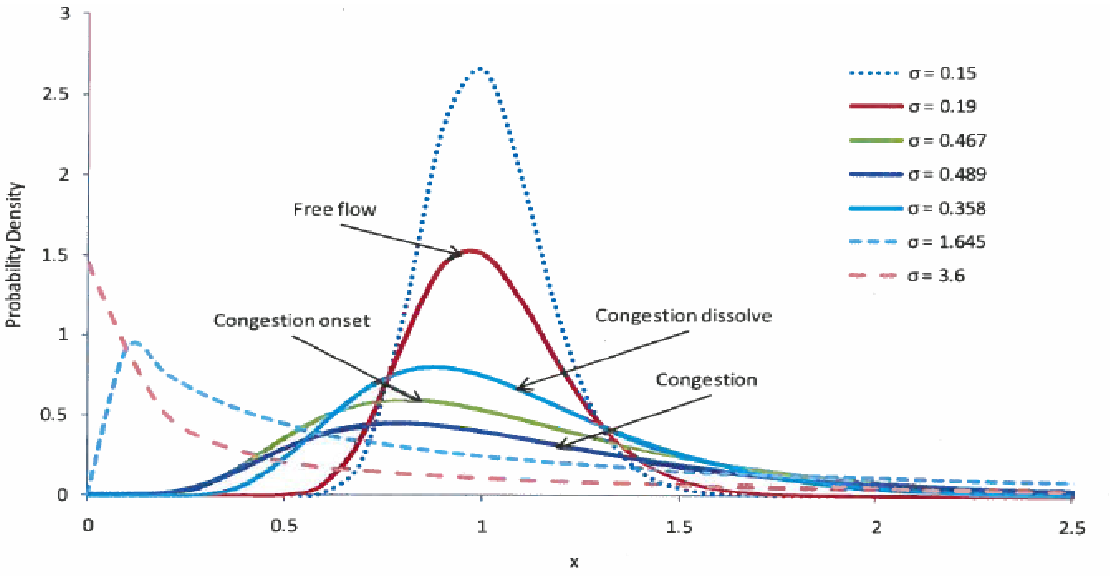


Figure 1: Probability Density Function of the Standard Lognormal Distribution

In 2010, Cambridge Systematics, Inc. in a research project (Project L03) conducted for the SHRP 2 Reliability entitled "Analytic Procedures for Determining the

Impacts of Reliability Mitigation Strategies" analyzed the effects of nonrecurring congestion such as incidents, weather, work zones, special events, traffic control devices, fluctuations in demand, and bottlenecks. This project defined reliability, explained the importance of travel time distributions for measuring reliability, and recommended specific reliability performance measures. This study reexamined the contribution of the various causes of nonrecurring congestion, especially those listed above. The research focused primarily on urban freeway sections although some attention was given to rural highways and urban arterials. Numerous actions that can potentially reduce nonrecurring congestion were identified with an indication of their relative importance. Models for predicting nonrecurring congestion were developed using three methods, all based on empirical procedures. The first involved before and after studies; the second was termed a "data poor" approach and resulted in a parsimonious and easy-to-apply set of models; the third was entitled a "data rich model" and used cross-section inputs including data on selected factors known to directly affect nonrecurring congestion. An important conclusion of the study is travel time reliability can be improved by reducing demand, increasing capacity, and enhancing operations.

In 2010, a research project conducted by Northwestern University entitled "Providing Reliable Route Guidance: Phase II" had the overarching goal to enhance travel reliability of highway users by providing them with reliable route guidance produced from newly developed routing algorithms that are validated and implemented with real traffic data. Phase I of the project (funded by CCITT in 2008) is focused on demonstrating the value of reliable route guidance through the development and dissemination of Chicago Testbed for Reliable Routing (CTR). Phase II aims at bringing the implementation of reliable routing technology to the next stage through initial deployment of CTR. The first objective in Phase II is to create a travel reliability inventory (TRI) of Northeastern Illinois using CTR by collaborating with public agencies such as Illinois Department of Transportation (IDOT), Chicago Transit Authority (CTA) and Chicago Traffic Management Authority (CTMA). TRI documents travel reliability indices (e.g., 95 percentile route travel times) between heavily-traveled origins-destination pairs in the region, which are of interest to not only individual travel decision-making, but also regional transportation planning and traffic operations/management. The second objective is to perform an initial market test in order to understand users' need for and response to reliability information and reliable route guidance. To these ends, the following research activities are proposed to further develop CTR: (1) Implement and test the latest reliable routing algorithms that are suitable for large-scale applications and (2) develop a web-based version of CTR and host the service at Northwestern University's Translab Website.

In 2010, Virginia Tech in a research project (Project L10) conducted for SHRP 2 Reliability entitled "Feasibility of Using In-Vehicle Video Data to Explore How to Modify Driver Behavior that Causes Non-Recurring Congestion" examined the causes of incidents on nonrecurring congestion and driver error on incidents and determined the feasibility of using in-vehicle video data to make inferences about driver behavior that would allow investigation of the relationship between observable driver behavior and nonrecurring congestion to improve travel time reliability.

This project examined existing studies that had used video cameras and other onboard devices to collect data, and it determined the potential for using these data to explore how to modify driver behavior in an attempt to reduce nonrecurring congestion. The research team made inferences to identify driver behaviors that contribute to crashes and near crashes, and they proposed countermeasures to modify those behaviors. The report provided technical guidance on the features and technologies, as well as supplementary data sets, which researchers and practicing professionals should consider when designing instrumented in-vehicle data collection studies. Also presented is a new modeling approach for travel time reliability performance measurement.

Though, these recent studies on the topic provide reasonable methodologies for travel time reliability, a generalized model which captures the different factors that influence travel time reliability such as posted speed, access density, arterial length, traffic conditions, signalized intersection spacing, roadway and intersection geometrics, and signal control settings is still lacking. Specially, there is a need that these factors be weighted according to their impacts.

2.2 Previous Travel Time Reliability Calculation Methods

The Federal Highway Administration is encouraging agencies to adopt travel time reliability measures to better manage and operate their transportation system. They came out with the following reliability calculation methods:

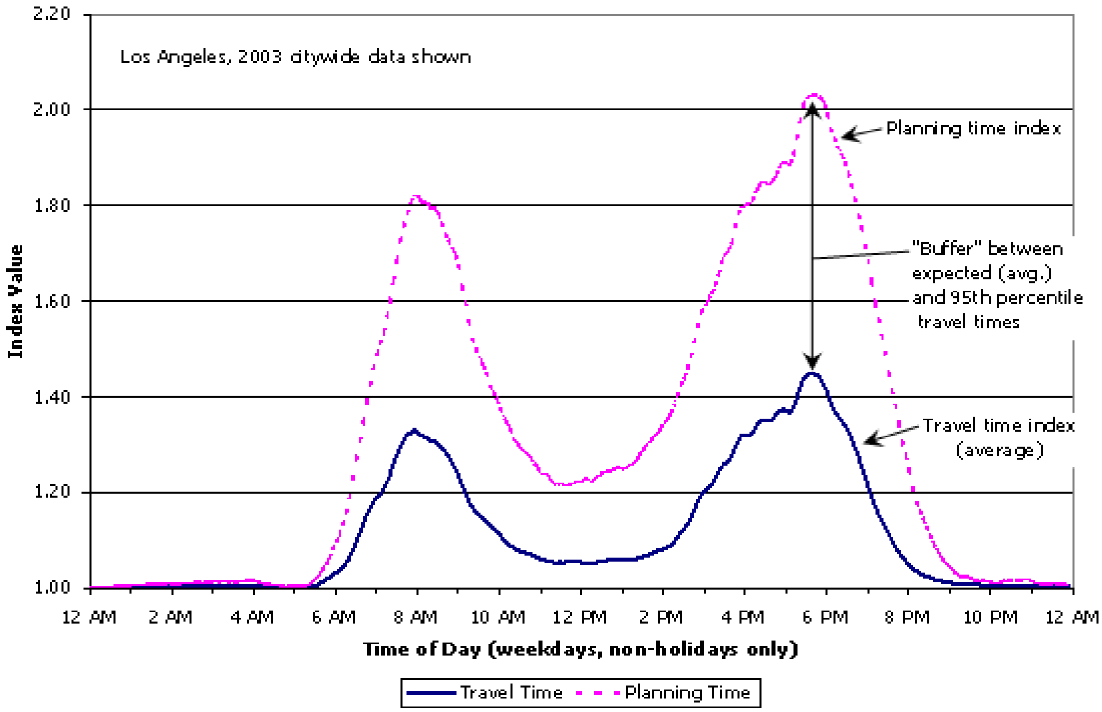


Figure 2: Reliability Measures Compared to Average Congestion Measures (Source: http://mobility.tamu.edu/mmp/)

- 90th or 95th Percentile Travel Times: how much delay will be on the heaviest travel days for specific travel trips or routes? The 90th or 95th percentile travel times are reported in minutes and seconds and should be easily understood by commuters familiar with their trips. This measure has the disadvantage of not being easily compared across trips, as most trips will have different lengths. It is also difficult to combine route or trip travel times into a subarea or citywide average.
- Travel Time Index: mean travel time it takes to travel during peak hours compared to free flow conditions, computed as mean travel time divided by free flow travel time.

- Buffer Index: represents the extra buffer time (or time cushion) that most travelers add to their average travel time when planning trips to ensure on-time arrival. This extra time is added to account for any unexpected delay. The buffer index is expressed as a percentage and its value increases as reliability worsens. The buffer index is computed as difference between 95th percentile travel time and mean travel time, divided by mean travel time.
- Planning Time Index: represents the total travel time that should be planned when an adequate buffer time is included. The planning time index differs from the buffer index in that it includes typical delay as well as unexpected delay. Thus, the planning time index compares near-worst case travel time to a travel time in light or free-flow traffic. Planning time index is computed as 95th percentile travel time divided by free-flow travel time.

For travelers who are familiar with everyday congestion (e.g., commuters), Buffer Time Index would be a preferred travel time reliability measure since it is based on average travel time; for those who are not familiar with that, planning time index may be preferred as it is based on free flow travel time (Pu, W., 2010).

- Frequency of congestion: the frequency when congestion exceeds some expected threshold**.** This is typically expressed as the percent of days or time that travel times exceed X minutes or travel speeds fall below Y mph. The frequency of congestion measure is relatively easy to compute if continuous traffic data is available, and it is typically reported for weekdays during peak traffic periods.

Traffic professionals have come to recognize the importance of travel time reliability because it better quantifies the benefits of traffic management and operation activities than simple averages and have, consequently, adopted other travel time reliability calculation methods.

- Standard Deviation: A widely employed measurement of variability or diversity used in statistics and probability theory. It shows how much variation or "dispersion" there is from the average (mean, or expected value). It is sometimes used as a proxy for other reliability measures and is a convenient measure when calculating reliability of travel time using classical or statistical models (Dowling et al., 2009). The standard deviation has the disadvantage of treating late and early arrivals with equal weight while the public cares much about late arrival. It is not either easily related to everyday commuting experiences.
- Coefficient of Variation: This is a ratio of standard deviation to the mean. The coefficient of variation has the same disadvantages as the standard deviation.
- Percent Variation: The average and standard deviation values combined in a ratio to produce a value that the 1998 California Transportation Plan calls percent variation. This is the form of the statistical measure coefficient of variation.

  Percent Variation= (Standard Deviation/Average travel time)*100%.

  Thus, mathematically, it has the same characteristics as the coefficient of variation. However, because the percent variation is expressed as a percentage of average travel time, it is easily understood by the public (Pu W., 2010).
- Failure Rate (Percent of On-Time Arrival): On-time arrival estimates the percentage of time that a traveler arrives on time based on an acceptable lateness

threshold.[16] Failure rate=100%-percent of on-time arrival. The threshold travel time to determine an on-time arrival ranges from 110 to 113 percent of average travel time.

- Florida Reliability Method: The Florida measure uses a percentage of the average travel time in the peak to estimate the limit of the acceptable additional travel time range.[17] The sum of the additional travel time and the average time define the expected time. Travel times longer than the expected time would be termed "unreliable." This calculation method has the disadvantage of using travel time rather than travel rate. One adjustment that might be needed for real-time monitoring systems is to use travel rate rather than travel time. Travel rate variations provide a length-neutral way of grading the system performance that can be easily calculated and communicated to travelers (Lomax et al., 2003).

  Florida Reliability Statistic (% of unreliable trips) =100% - (percent of trips with travel times greater than expected).

- The Urban Mobility Study Report in "The Keys to Estimating Mobility in Urban Areas" suggested a threshold of 10 percent higher than the average travel time (or travel rate)[18] for travel time reliability. However, the 10 percent late arrival has the disadvantage of being relatively conservative for some applications.

- Stephen Clark and David Watling used the probability distribution of the actual values of the performance measure to define unreliability. For them, the planning

---

[16] Cambridge Systematics, Inc.; Dowling Associates, Inc; System Metrics Group, Inc.; Texas Transportation Institute. Cost-Effective Performance Measures for Travel Time Delay, Variation, and Reliability. Washington, D.C.: TRB, 2008. NCHRP Report 618.

[17] Florida Department of Transportation. Florida's Mobility Performance Measures Program. Summary Report. Office of state Transportation Planner, Tallahassee, Florida, August 2000

[18] The Keys to Estimating Mobility in Urban Areas: Applying Definitions and Measures That Everyone Understands, 1998 (http://mobility.tamu.edu).

state (a representative set of assumptions concerning the state of the road network and demand data that is chosen subjectively by the planner) occurs when the performance measure equals the mode of around 1; the critical value is defined as a tolerance of 400 percent above the performance measure value in the planning state, yielding to a critical value of 5. Then they defined unreliability, for example, in terms of the probability of exceeding the critical value Pr (*M*>5), i.e., the area under the curve in the range labeled “degraded performance” (see Figure 3). Thus in percentage terms, the reliability is:

$\rho=100\ (1-\Pr\ (M>5))\ \%.$

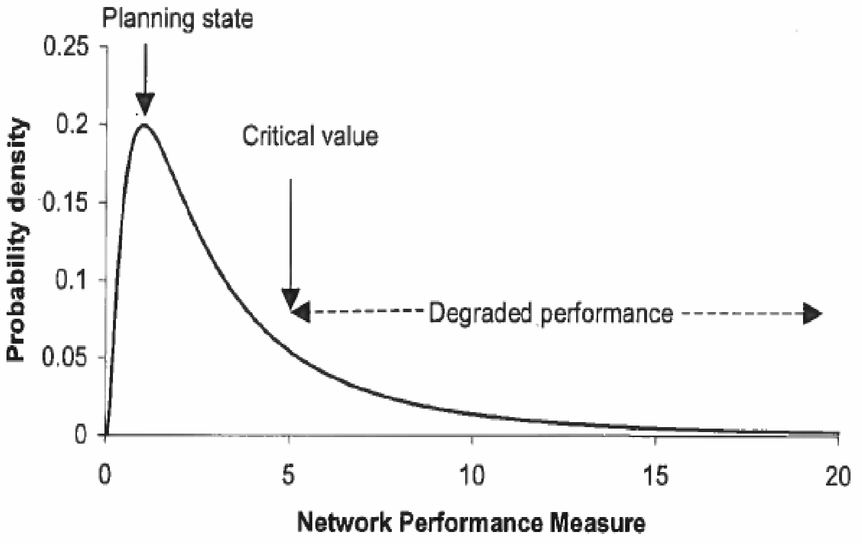


Figure 3: Performance Measure Distribution

The different travel time calculation measures are summarized in Table 1 and the advantages of the selected calculation measure for the dissertation are explained afterwards.

Table 1: Travel Time Reliability Measures Recommended by Different Sources[19]

Travel Time Reliability Measures	**Lomax, et al. (2003)**	**FHWA Guide (2006)**	**NCHRP Report 618 (2008)**	**SHRP 2 (2008)**	**California Transportation Plan (1998)**
95th or other percentile travel time		√			
Standard Deviation		X	X		
Coefficient of Variation		X	X		
Percent Variation	√		√		√
Skew Statistic				√	
Buffer Index	√	√	√	√	
Planning Time Index		√	√	√	
Frequency of Congestion		√			
Failure Rate (Percent On-Time Arrival)			√	√	
Misery Index	√		√	√	

"√ ": Encouraged; "X": Discouraged

Among above Travel Time Reliability Measures, Buffer Index (Buffer Time) was selected as the calculation method for the dissertation for the following reasons:

1) It is a well-defined traditional statistic that can be easily calculated with classical statistic methods.

---

[19] Table Modified from "Analytic Relationship between Travel Times Reliability Measures", Pu, W., 2010

2) “Reliability” itself is a term of art that may have little meaning to the traveling public (Texas A&M University Traveler Information and Travel Time Reliability). Travelers do obtain considerable information about reliability from their own daily experiences. However, an overall lack of knowledge exists about what reliability information is useful to travelers, how best to communicate it to them, how reliability information impacts traveler choices and demand at given times on particular facilities, and how communicating information about reliability affects system performance, particularly in terms of recurrent and nonrecurring highway congestion.[20] The buffer index (buffer time) could be used as an effective communication tool since nontechnical audiences can easily understand the term.
3) It is typically reported for weekdays during peak traffic periods.
4) It is recommended by The FHWA (Federal Highway Administration) Guide (2006), NCHRP (National Cooperative Highway Research Program) Report 618 (2008), Lomax, et al. (2003), and SHRP (Strategic Highway Research Program) 2 (2008).
5) It has been mainly applied on freeways and will be experimented on arterials.
6) Finally, from the road user perspective (demand side) a key focus in travel time reliability is the net effect on a user’s trip through the network, i.e. on travel from origin to destination. The buffer time could help the advised commuter track his daily travel time and adjust his driving time accordingly.

---

[20] Texas A&M University, Traveler Information and Travel Time Reliability, 2010.

Chapter 3-Methodology

From Sensys Networks aggregate output record, 3,503 travel time data sets were selected for 2 consecutive weeks in 5 minutes interval for statistical analysis. The data processing was conducted in Microsoft EXCEL (from Q1 Macros 2010) with proper data arrangements among different worksheets. These data are integrated into the reliability equation to determine the reliable travel times based on the travel time thresholds. The reliable travel times are integrated along with the influencing factors (described below) into the linear regression equations to generate the correlation among factors and the equation for the model.

3.1 Influencing Factors

- Access Density, which is the number of access points divided by the length of the segment, refers to the legal limitation or restriction of access from private properties to public rights-of-way. The quality of flow, capacity, travel time, Level of Service, and safety of a highway can be greatly affected by the degree and manner of access control along it.
- Annual Average Daily Traffic (AADT) is a measure used primarily in transportation planning and transportation engineering. AADT is the total volume of vehicle traffic of a highway or road for a year divided by 365 days. AADT is a useful and simple measurement of how busy the road is and has influencing impacts on average travel time and travel speed.

- Posted Speed is a primary factor in highway design and is usually equal to or lowers than the design speed. The level of service provided by a facility is directly related to the speeds of operation provided by it. When roads are planned, the selected design/posted speed is based on several factors, including but not limited to: geometric design of road features, travel time, safety, and anticipated traffic volume. The design/posted speed may also depend on the topography, particularly in cases where limited funds are available. The design/posted speed should be compatible with the expectations of nearly all drivers and consistent with the functional classification and location of the highway or street.
- Intersection Traffic Control consists of traffic control signals that offer an effective method for controlling traffic at an intersection, and they eliminate many conflicts to different approaches at different times. Traffic control signals are usually described as either pre-timed or traffic-actuated. Each may be used in isolated (independent) or signal-system operations. When properly installed and operated at appropriate locations, traffic signals provide a number of significant benefits:
    1) With appropriate physical designs, control measures, and signal timing, the capacity of critical intersection movements is increased.
    2) When properly coordinated, signals can provide for nearly continuous movement of through traffic along an arterial at a designed speed under favorable traffic conditions.

3) Traffic signals interrupt heavy traffic at intervals to permit other traffic, (vehicular or pedestrian) to cross.

At the same time, misapplied or poorly designed signals can cause excessive delays, signal violations, increased accidents (particularly rear-end accidents), and drivers rerouting their trips to less appropriate routes.

- Roadway Geometry involves the functional layout of travel lanes, curb ramps, crosswalks, turning lanes, number of intersection legs, and bike lanes in both horizontal and vertical dimensions. Roadway geometry has a profound influence on roadway safety and operational performance for all road users.
- Time of Day is an influencing factor for travel time in urban congested areas. In these areas, drivers are familiar with congestion and they plan their travel time accordingly. Many drivers either adjust their schedules or budget extra time to allow for traffic delay particularly during peak driving times.

These influencing factors defined above will fluctuate based on the traffic demand/supply to interact with the travel time reliability. The interaction is illustrated in Figure 4 in the following page.

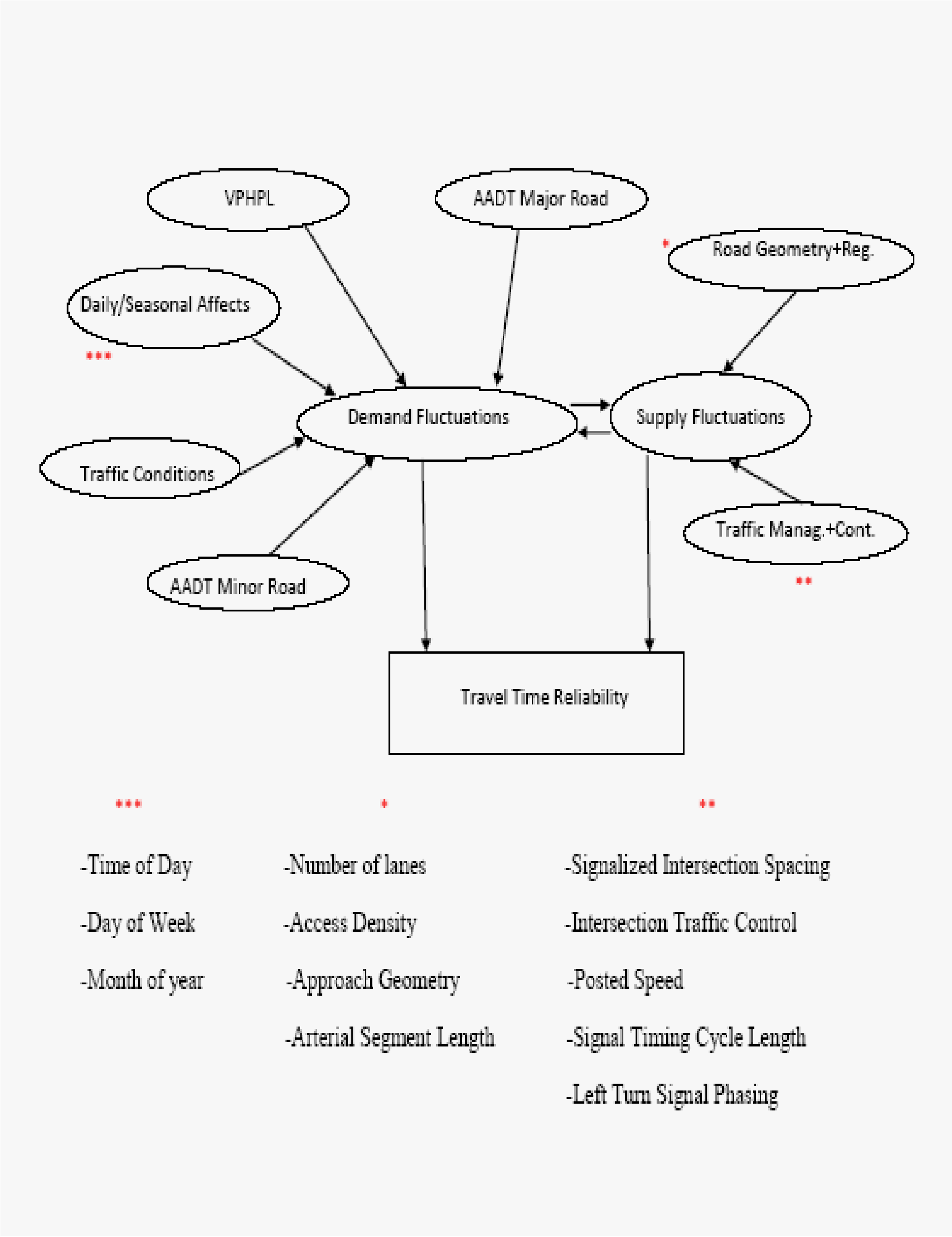


Figure 4: Factors Affecting Travel Time Reliability

3.2 Statistical Methods and Analysis

According to the American Heritage Dictionary of the English Language (New College Edition, 1981), statistics is the mathematical science dealing with the collection, analysis, and interpretation of numerical data using the theory of probability, especially with methods for drawing inferences about characteristics of a population from examination of a random sample. Statistical analysis refers to a collection of methods used to process large amounts of data and report overall trends. Statistical methods are used in research to summarize or describe a collection of data, especially to communicate the results of experiments. In addition, patterns in the data may be modeled (formalization of relationships between variables in the form of mathematical equations) in a way that accounts for randomness and uncertainty in the observations and are then used to draw inferences about the process or population being studied. Statistical analysis and statistical methods are particularly useful in describing and illustrating some of the tools commonly used for transportation data especially in travel time reliability monitoring system. As outlined by North Carolina State University in a study conducted for Transportation Research Board, SHRP 2 entitled" Monitoring Programs for Mobility and Travel Time Reliability", 2010:

> ……Combining travel time data with data on the other (explanatory) variables is important in the design of a reliability monitoring system. The design of a travel time reliability monitoring system requires the use of statistics to develop a sampling plan for locating traffic detectors and collecting travel time data—this includes determining appropriate geographic and time scales. Statistical methods also provide insight

regarding the selection, validation, and application of appropriate measures of travel time reliability, as well as for estimating models of travel time reliability that reflect key factors.

3.2.1 Travel Time Reliability Calculation Method

Buffer time, a reliability measure recommended by USDOT, NCHRP, SHRP2, and Lenox et al. is selected for the dissertation. The buffer time represents the extra time (buffer or cushion time) that most travelers add to their average travel time when planning trips to ensure on-time arrival. The buffer index, another reliability measure, is expressed as a percentage and its value increases as reliability gets worse. A segment is considered reliable when travel time threshold is equal to or lowers than the summation of the buffer time and the average travel time.

The buffer index is computed as follows:

$$\textit{Buffer index (\%)} = \frac{95^{th}\ percentile\quad travel\quad time(\sec.) - average\quad travel\quad time(\sec.)}{average\quad travel\quad time(\sec.)} \qquad [1]$$

where 95^{th} percentile travel time indicates how bad delay will be on the heaviest travel days and is a translation of a standard "I can be late to work 1 day a month (1 day out of 20± work days) without getting into too much trouble" (Lomax et al., 2003).

The buffer time is computed as follows:

$$\textit{Buffer time (seconds)} = 95^{th}\ \textit{percentile travel times (sec.)-average travel time (sec)} \qquad [2]$$

From [2], travel time reliability threshold (in seconds) for the dissertation is deducted as follows:

$$\text{Travel time threshold (reliability)} \leq \text{buffer time} + \text{average travel time} \qquad [3].$$

3.2.2 Correlation among Reliable Travel Times and Influencing Factors

Correlation among reliable travel times and influencing factors is calculated by using ANOVA (Analysis of Variance) and Pearson Product Moment. In statistics, the Pearson product-moment correlation coefficient (sometimes referred to as the MCV or PMCC) (r) measures the strength and the direction of a linear relationship between two variables X and Y. When measured in a population the Pearson Product Moment correlation is designated by the Greek letter rho (ρ). When computed in a sample, it is designated by the letter r and is sometimes called "Pearson's r." Pearson's correlation reflects the degree of linear relationship between two variables. It ranges from “-1 to +1”. This range helps understand the strength of relationship – rather, the strength of linear relationship between the variables. The closer the coefficients are to +1.0 or –1.0, the greater the strength of the linear relationship. Correlation coefficients in the range of -1.0 to - 0.65 or 1.0 to 0.65 mean that the variables are highly correlated. In the particular case of high correlation among variables, one variable provides no additional information over and above its perfectly correlated counterpart. A detailed analysis of the multicollinearity among independent variables will be performed to determine whether some variables should be dropped from the model.

The Pearson Product Moment correlation is computed as follows:

$$r_{xy} = \frac{n\sum XY - \sum X \sum Y}{\sqrt{\left[n\sum X^2 - \left(\sum X\right)^2\right] * \left[n\sum Y^2 - \left(\sum Y\right)^2\right]}} \qquad [4]$$

where ***n*** = number of paired observations; ***X***=Variable A (Reliable Travel Times, or Influencing Factors); and ***Y*** = Variable B (Influencing Factors).

3.2.3 Linear Relationship between Dependent and Independent Variables

The linear relationship between travel time threshold (dependent variable) and the influencing factors (independent variables) is computed by using the multiple linear regression equation.

Linear regression is one of the most widely studied and applied statistical and econometric techniques for the following reasons:

- The linear regression model is suitable for modeling a wide variety of relationships between variables.
- The linear regression models are often suitably satisfied in many practical applications, such as the following assumptions:

1) Functional form: $Y_i = \beta_o + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \ldots\ldots + \varepsilon_i$

2) Zero mean of disturbances: $E[\varepsilon_i] = 0$

3) Homoscedasticity of disturbances: $VAR\ [\varepsilon_i] = \sigma^2$

4) Non-autocorrelation of disturbances: $COV\ [\varepsilon_{i,}\ \varepsilon_j] = 0$ if $i \neq j$

5) Uncorrelated nature of regressor and disturbances: $COV\ [X_i, \varepsilon_j] = 0$ for i and j

6) Normality of disturbances: $\varepsilon_i = N\ (0, \sigma^2)$.

- Numerical estimation of regression models is relatively easy, and software for estimating models is readily available in numerous “non-specialty” software packages.

The linear regression equation will be multiple and take the following form:

$$\begin{pmatrix} Y_1 \\ : \\ : \\ Y_n \end{pmatrix} = \begin{pmatrix} 1 & X_{11}\, X_{21}\, X_{31} \ldots X_{n1} \\ : & \ldots \\ : & \\ 1 & X_{n1}\, X_{n2}\, X_{n3} \ldots X_{np} \end{pmatrix} \begin{pmatrix} \text{ß}_0 \\ \\ : \\ \text{ß}_p \end{pmatrix} \qquad [5]$$

where $\boldsymbol{Y_i}$ to $\boldsymbol{Y_n}$ are the reliable travel times (travel time thresholds); $\boldsymbol{X_i}$ to $\boldsymbol{X_n}$ the different factors affecting these travel times, and $\boldsymbol{\text{ß}_0}$ to $\boldsymbol{\text{ß}_p}$ the coefficients of the factors.

From this equation R^2, adjusted R^2, and F values will be determined.

R^2 can be thought of as the proportionate reduction of total variation accounted for by the independent variables (X). It is commonly interpreted as the proportion of total variance explained by X.

Adjusted R^2 is used to account for the changes in the degrees of freedom as a result of different numbers of model parameters and allows for a reduction in adjusted R^2 as additional, potentially insignificant variables are added.

Another measure of assessing model fit is the generalized F test. This approach is a general and flexible approach for testing the statistical difference between competing models.

3.2.4 The Wrong Signs in the Linear Regression Model

In a multiple linear regression model coefficients often have signs that are contrary to expectations. There is a variety of reasons that multiple linear regression produces the “wrong sign” for some coefficients (Mullet, 1976):

- Computational error. Some computational procedures for computing least squares have problems with precision when the magnitudes of variables differ drastically. To avoid this problem, it is recommended to convert variables to standard form (e.g., 0 mean and unit variance) for calculations and convert back to the original form for displaying the coefficients (Pazzani & Bay, 1999).
- Coefficients that do not significantly differ from zero. In this case, the sign of the coefficient does not matter because it is too small to significantly affect the equation. One recommended way to avoid this problem is to eliminate the irrelevant variables from forward stepwise regression methods where a variable is included in the model only if it significantly improves the fit of the model of the data (Draper & Smith, 1981).
- Multicollinearity. Multicollinearity causes inflated standard errors, which in turn make it more likely an “incorrect sign”. When two or more explanatory variables are not independent, the sign of the coefficients of one of the variables may differ from the sign of that coefficient if the variable were the only explanatory variable. One approach to deal with this problem is to manually eliminate some of the variables from the analysis (Pazzani & Bay, 1999).

- Nonlinearity. If the true relationship between the dependent variable and the explanatory is nonlinear, the coefficients can be biased with changing (different or wrong) signs.
- The variable in question is a proxy for another variable. In some cases the variable in question may be highly correlated with other variables which have been excluded from the analysis. Such variables are also known as “confounding variables”. The wrong sign might be attributable to an excluded confounding variable (Rinott & Tam, 2003).
- Improper interpretation of parameters. The interpretation of a parameter is entirely dependent upon the model in which the parameter appears.

Even with “incorrect signs”, the model still may be useful for prediction in the region of X-values from which the model was built, e.g., the model is still useful as a predictive model, as long as the extrapolation does not go beyond the region of the data.

3.3 Alternative Models

3.3.1 Simultaneous Equation Models (SEM)

Simultaneous equation models are a form of statistical model in the form of a set of linear simultaneous equations. They are often used in interrelated transportation data modeling, such as the interrelation between travel time from home to an activity and the duration of the activity and the interrelation of average vehicle speeds by lane with the vehicle speeds in adjacent lanes.

Unlike the single-equation model in which a dependent (*Y*) variable is a function of independent (*X*) variables, other *Y* variables are among the independent variables in each SEM equation. The *Y* variables in the system are jointly (or simultaneously) determined by the equations in the system.

Compare the usual single equation,

$$Y=ß_0+ß_1X_1+\varepsilon$$

to a simple, two-equation SEM:

$$Y_1=\alpha_0+\alpha_1Y_2+\alpha_2X_1+\varepsilon_1$$

$$Y_2=Y_0+Y_1Y_1+\varepsilon_2$$

The simplest and the most common estimation method for the simultaneous equations model is the so-called two-stage least square method. This method is an equation-by-equation technique, where the endogenous regressors on the right-hand side of each equation are being instrumented with the regressors *X* from all other equations. The method is called “two-stage” because it conducts estimation in two steps (Greene, 2003).

However, interrelated systems of equations can cause serious estimation problems if their interrelated structure is not considered. These problems arise because estimation of equation systems using Ordinary Least Squares (OLS) violates a key OLS assumption in that a correlation between regressors and disturbances will be present because not all independent variables are fixed in random samples (one or more of the independent variables will be endogenous and OLS estimates will be erroneous) (Washington, Karlaftis, & Mannering, 2003). In addition, the general issue of endogeneity resulting from simultaneous equation models is often ignored in the analysis of transportation data. Ignoring endogeneity will lead to erroneous conclusions and inferences.

3.3.2 Count Data Models

Count data consist of non-negative integer values and are encountered frequently in the modeling of transportation related-phenomena. Examples of count data variables in transportation include the number of driver route changes per week, the number of trip departure changes per week, drivers' frequency of use of Intelligent Transportation Systems (ITS) technologies over the same period, number of vehicles waiting in queue, and the number of accidents observed on road segments per year. Count data regression is as simple as estimation in the linear regression model, if there are no additional complications such as endogeneity, panel data, etc. (Cameron, 2009) A common mistake is to model count data as continuous data by applying standard least squares regression. This is not correct because regression models yield predicted values that are non-integers and can also predict values that are negative, both of which are inconsistent with count data (Washington et al., 2003). These limitations make standard regression analysis inappropriate for modeling count data without modifying dependent variables.

Count data are properly modeled by using a number of methods, the most popular of which are Poisson and negative binomial regression models.

3.3.3 The Poisson Distribution

The Poisson distribution or Poisson law of small numbers is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time and/or space if these events occur with a known average rate and independently of the time since the last event. The Poisson distribution can also be used for the number of events in other specified intervals such as distance, area or volume. One requirement of the Poisson distribution is that the mean of the count process equals its variance. When the variance is significantly larger than the mean, the data are said to be overdispersed.

The Poisson probability distribution is computed as follows:

$$\Pr(Y = y \mid \lambda) = \frac{e^{-\lambda}\lambda^{y}}{y!} \quad \text{for } y = 0,1,2,\ldots$$

Poisson is a one parameter λ (lambda), which is the mean and the variance or expected value of a Poisson distribution.

3.3.4 The Negative Binomial Regression Model

The Negative Binominal regression model can be used if data are overdispersed. This model is then more efficient than Poisson, but in practice the efficiency benefits over Poisson are small. However, the negative binomial model should be used if one wishes to predict probabilities and not just model the mean**.**

The Negative Binomial Regression equation is computed as follows:

$$\Pr(Y = y \mid \lambda, \alpha) = \frac{\Gamma(y + \alpha^{-1})}{y!\,\Gamma(\alpha^{-1})} \left(\frac{\alpha^{-1}}{\alpha^{-1} + \lambda} \right)^{\alpha^{-1}} \left(\frac{\lambda}{\alpha^{-1} + \lambda} \right)^{y}$$

The negative binomial distribution has two parameters: λ, which is the mean or expected value of the distribution and α, which is the over dispersion parameter. When α = 0 the negative binomial distribution is the same as a Poisson distribution.

3.3.5 Discrete Outcome Models

Discrete or nominal scale data often play a dominant role in transportation because many interesting policy-sensitive analyses deal with such data. Discrete choice models are statistical procedures that model choices made by people among a finite set of alternatives. The attributes of the alternatives can differ over people; e.g., cost and time for travel to work by car, bus, and rail are different for each person depending on the location of home and work of that person. Discrete choice models have been used to examine the choice of which car to buy (Train & Winston, 2007), where to go to college, (Fuller, Manski, & Wise, 1982) which mode of transport (car, bus, rail) to take to work (Train,1978), the number of vehicles a household chooses to own (Train, 1986) among numerous other applications. While regression analysis examines “how much”, discrete choice analysis examines “which”. In addition, discrete choice analysis examines situations in which the potential outcomes are discrete, such that the optimum is not characterized by standard first-order conditions.

The discrete outcome models are most often estimated using standard maximum likelihood procedure, such estimation referred to as a Probit regression.

Suppose response variable Y is binary, that it can have only two possible outcomes, which denote as 1 and 0. For example, Y may represent presence/absence of a certain condition, success/failure of some device or answer yes/no on a survey. A vector h of regressors X is assumed to influence the outcome Y. Specifically, the model takes the following form:

$$Pr\ (Y=1/X) = \Phi\ (X'\beta),$$

where Pr denotes probability, and Φ is the Cumulative Distribution Function (CDF) of the standard normal distribution. The parameters β are typically estimated by maximum likelihood.

Binary and Multinomial Probit Models are the most common discrete outcome models. A distinction is often drawn between binary models (models that consider two discrete outcomes) and multinomial models (models that consider three or more discrete outcomes) because the derivation between the two can vary significantly (Washington et al., 2003).

As described above, these alternative models to the linear regression are widely used and applied in many transportation data analysis and modeling. However, it is obvious that the linear regression is most suited for modeling linear relationships between dependent and independent variables.

3.4 Different Steps for the Model Equation

1) Collect travel times data and select potential contributing factors.
2) Establish Travel Time Reliability Thresholds and run the single linear regression to determine the correlation among factors.
3) Determine reliable travel times (travel time thresholds).
4) Run multiple linear regression to eliminate the non-contributing factors and build the linear regression model.
5) Validate the model.
6) Report graphically the travel time reliability for the system.
7) Verify the generality and robustness of the model
8) Develop a list of scenario for Marginal Effects.
9) Provide guidance on Transportation Planning, Roadway Design, Traffic Design, Access Management, and Traffic Operations features.

The model framework is illustrated in Figure 5.

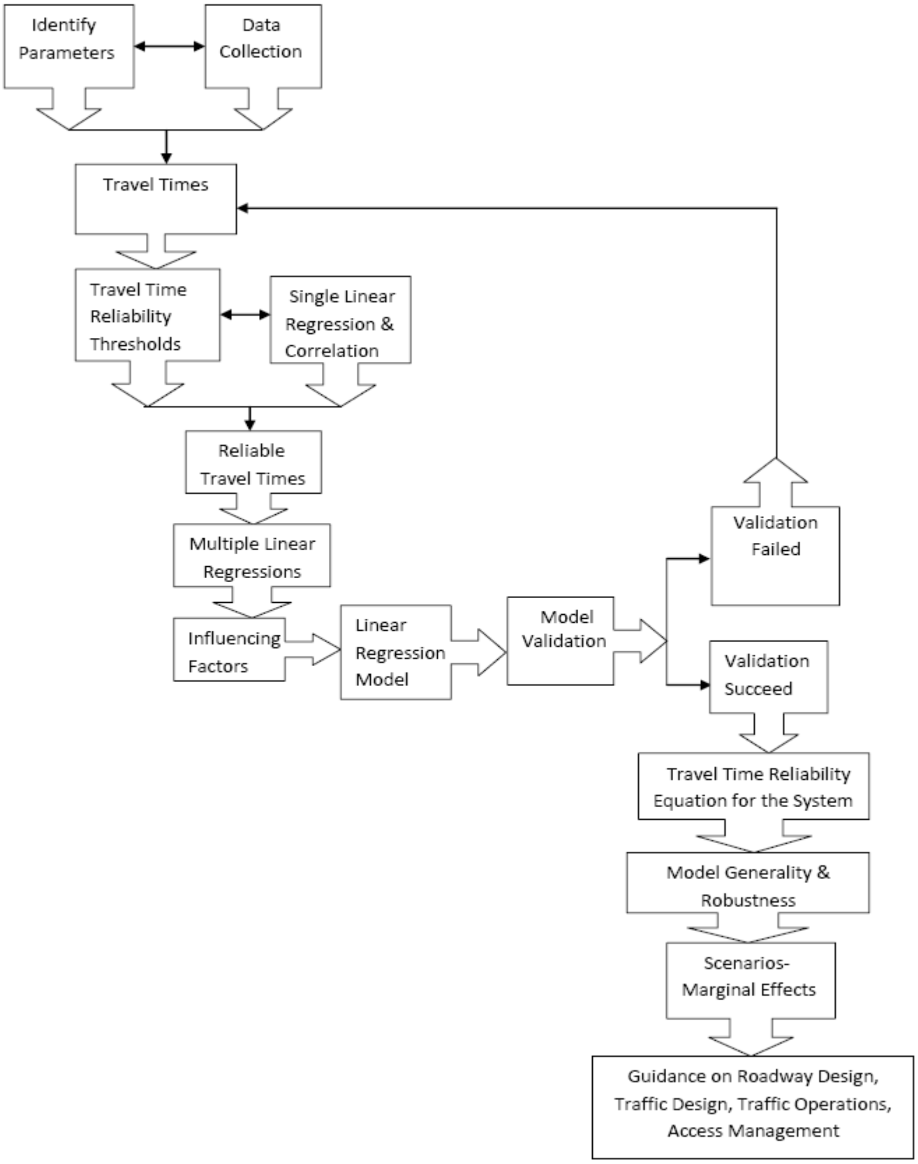
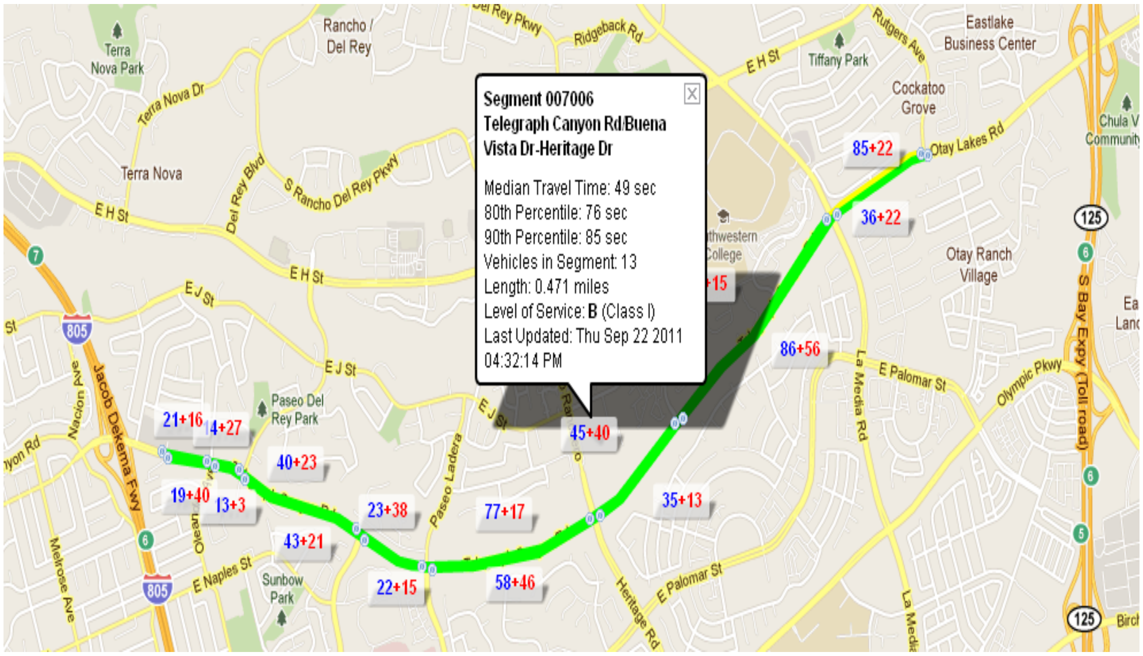


Figure 5: Model Framework

Chapter 4- Data Collection

4.1 Geographic Areas

A portion of Telegraph Canyon, a major urban arterial of 3.76 miles long located in Chula Vista County, CA was selected for the data analysis. The selected portion (from Rutgers Avenue to Halecrest Dr./ Canyon Plaza) is a West/East through route that consists of 8 segments and 9 signalized intersections and is connected to two access controlled corridors (South Bay Expy-125 and Jacob Dekema Fwy I-805). This is a six lane divided roadway with divers traffic and geometric characteristics, adjacent land use and development features. Additional lanes are available for the turning movements at intersection approaches and vehicles-actuated signal timing plans are operated in coordination mode for all intersections. Figure 6 highlights the 3. 76 mile corridor (in green on the map) and the travel time data (median travel time, 80th and 90th percentiles, vehicles in segment, and Level of Service) for segment # 7006. In addition, Figure 7 shows the geometric layout (number of lanes for the major road and the cross streets, number of exclusive right and left turn lanes, number of intersection legs) of the corridor and the different segment attributes are illustrated in Table 2.



Segment 007006
Telegraph Canyon Rd/Buena Vista Dr-Heritage Dr

Median Travel Time: 49 sec
80th Percentile: 76 sec
90th Percentile: 85 sec
Vehicles in Segment: 13
Length: 0.471 miles
Level of Service: **B** (Class I)
Last Updated: Thu Sep 22 2011 04:32:14 PM

Figure 6: Telegraph Canyon Rd, Chula Vista County, CA
(Source: http://www.sensysnetworks.com/traveltime)

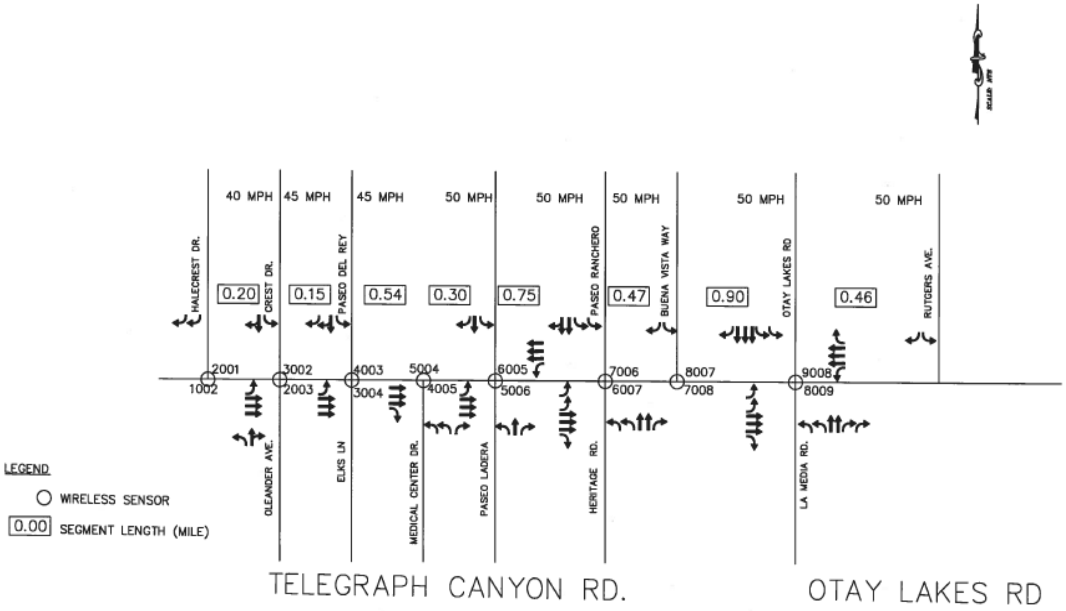


Figure 7: Telegraph Canyon Rd-Geometric Design Layout

Table 2: Segment Attributes

Segment Number	**From**	**To**	**Length (mile)**	**AADT**	**Posted Speed**	**Driving Direction**
009008	Rutgers Ave	La Media Rd	0.46	45508	50	Westward
008007	La Media Rd	Buena Vista Way	0.90	40279	50	
007006	Buena Vista Way	Paseo Ranchero (Heritage Rd)	0.47	48393	50	
006005	Paseo Ranchero (Heritage Rd)	Paseo Ladera	0.75	55760	50	
005004	Paseo Ladera	Medical Center Dr	0.30	52230	50	
004003	Medical Center Dr	Paseo Del Rey	0.54	63250	45	
003002	Paseo Del Rey	Crest Dr. (Oleander Ave)	0.15	65890	45	
002001	Crest Dr. (Oleander Ave)	Halecrest Dr (Canyon Plaza)	0.20	65583	40	
001002	Halecrest Dr (Canyon Plaza)	Crest Dr. (Oleander Ave)	0.20	65583	40	Eastward
002003	Crest Dr (Oleander Ave)	Paseo Del Rey	0.15	65890	45	
003004	Paseo Del Rey	Medical Center Dr	0.54	63250	45	
004005	Medical Center Dr	Paseo Ladera	0.30	52230	50	
005006	Paseo Ladera	Paseo Ranchero (Heritage Dr.)	0.75	55760	50	
006007	Paseo Ranchero (Heritage Dr.)	Buena Vista Way	0.47	48393	50	
007008	Buena Vista Way	La Media Rd	0.90	40279	50	
008009	La Media Rd	Rutgers Ave	0.46	45508	50	

4.2 Time Elements

Several time elements are considered for this dissertation:

- Month of Year
- Days of the Week
- Time Period or Time of Day

4.2.1 Month of the Year

For the purpose of this dissertation, the month of May, which is commonly considered "average" or "typical" annual traffic condition for this area, was selected.

4.2.2 Days of the Week

This dissertation is focused on the middle weekdays (i.e., Tuesday, Wednesday, and Thursday) for data collection. Monday, Friday, and holidays are excluded because of their high variation from typical day-to-day operating conditions during the middle of the week.

4.2.3 Time Periods

- Morning Peak Period: between 6:00 am to 9:00 am
- Afternoon Peak Period: between 4:00 pm to 7:00 pm

These time periods correspond to the local traffic condition and congestion patterns for the geographic area considered.

4.3 Data Collection Method

Collection and reduction of traffic data covers a wide range of techniques and technologies from simple manual techniques (often aided by a variety of handheld or other devices for recording the data) to complex use of the ever-expanding technologies of sensors, detectors, transmission, and computer equipment (Roess, Prassas, et McShane, 2010). Travel times data used for this dissertation are from Sensys Networks archives. For the ATTS (Arterial Travel Time System), Sensys Networks implements VD240 wireless vehicle detention system, which is easily scalable from stop bar detection to advance detection with the addition of a few in-pavement sensors. Arrays of

16 wireless sensors (a sensor comprising an array of five 3 in-cube magnetic nodes is embedded in the pavement at two ends of a single lane in the segment), 8 in each direction of traffic flow, are installed at intervals along Telegraph Canyon Road (from Rutgers Avenue to Halecrest Dr. /Canyon Plaza). As vehicles pass over sensors, they are assigned a unique, anonymous identifier (from their magnetic signatures), wirelessly transmitted to a nearby Access Point, before backhaul to a central office or Traffic Management Center (Figure 8). The Access Point matches the signatures from the sensors: if a match is made, the corresponding travel time is found. Integrated into Google Maps for congestion monitoring up to 70% of vehicles are correctly re-identified as opposed to single digit match rates from other probe technologies. Higher match rates means real-time speed and provides the following advantages:

- Reduces user error by eliminating manual data collection.
- Improves quality of data collected.
- Increases amount and type of data collection.
- Displays complete distribution of travel time (not just averages), number of vehicles in segment, Level of Service, 80th & 90th percentiles (Figures 9 and 10).
- Updates travel time data in minutes.
- Integrates into Google Maps for congestion monitoring.
- Measures and reports historical travel times for analysis.
- Eliminates the need for probe vehicle run because up to 70% of vehicles are correctly re-identified.
- Provides an accurate real-time estimate of the travel time distribution and traffic counts.

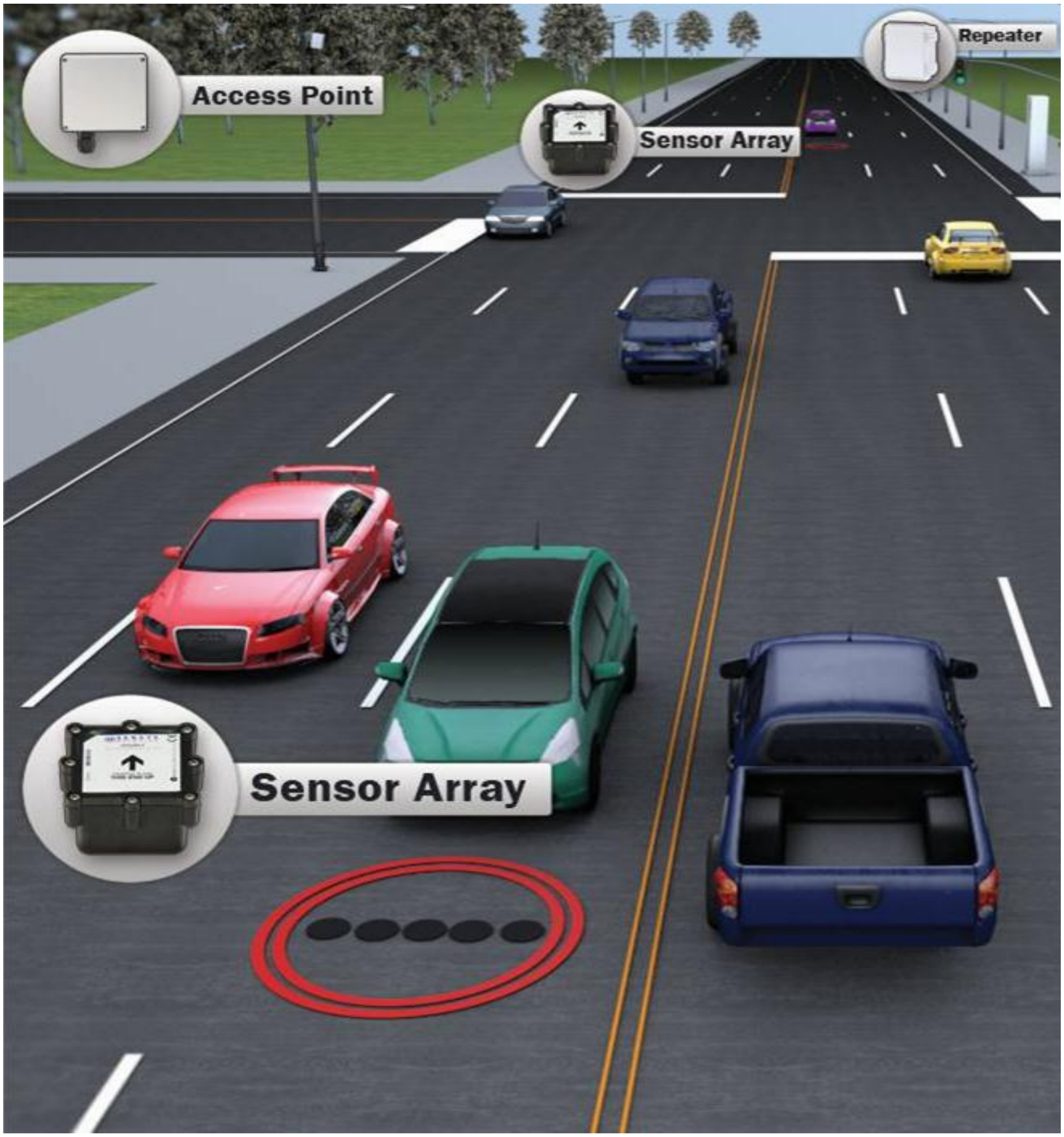


Figure 8: Wireless Sensors and Access Points Deployed for ATTS
(Source: http://www.sensysnetworks.com/traveltime)

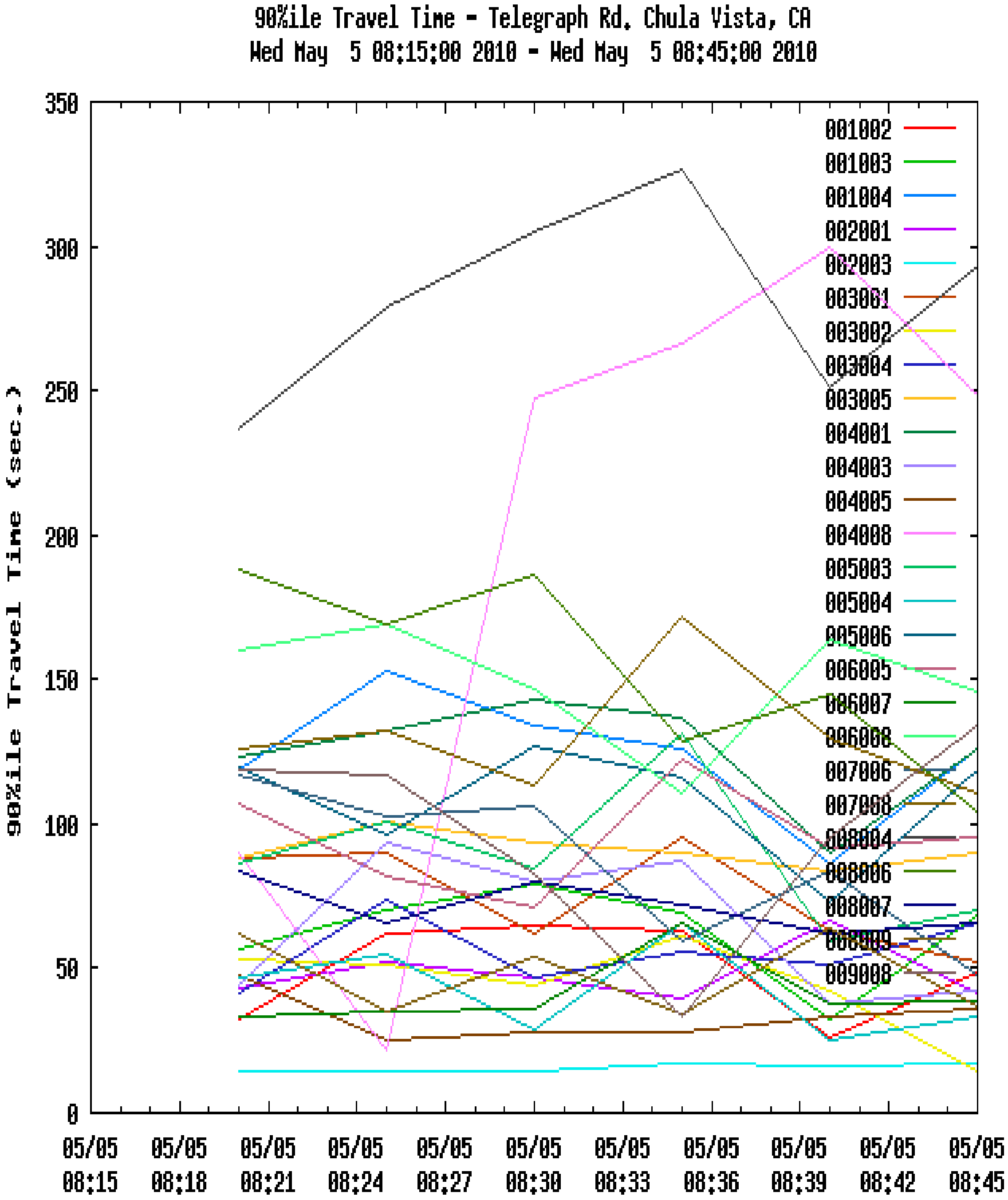


Figure 9: 90th Percentile Travel Time for ATTS
(Source: http://www.sensysnetworks.com/traveltime)

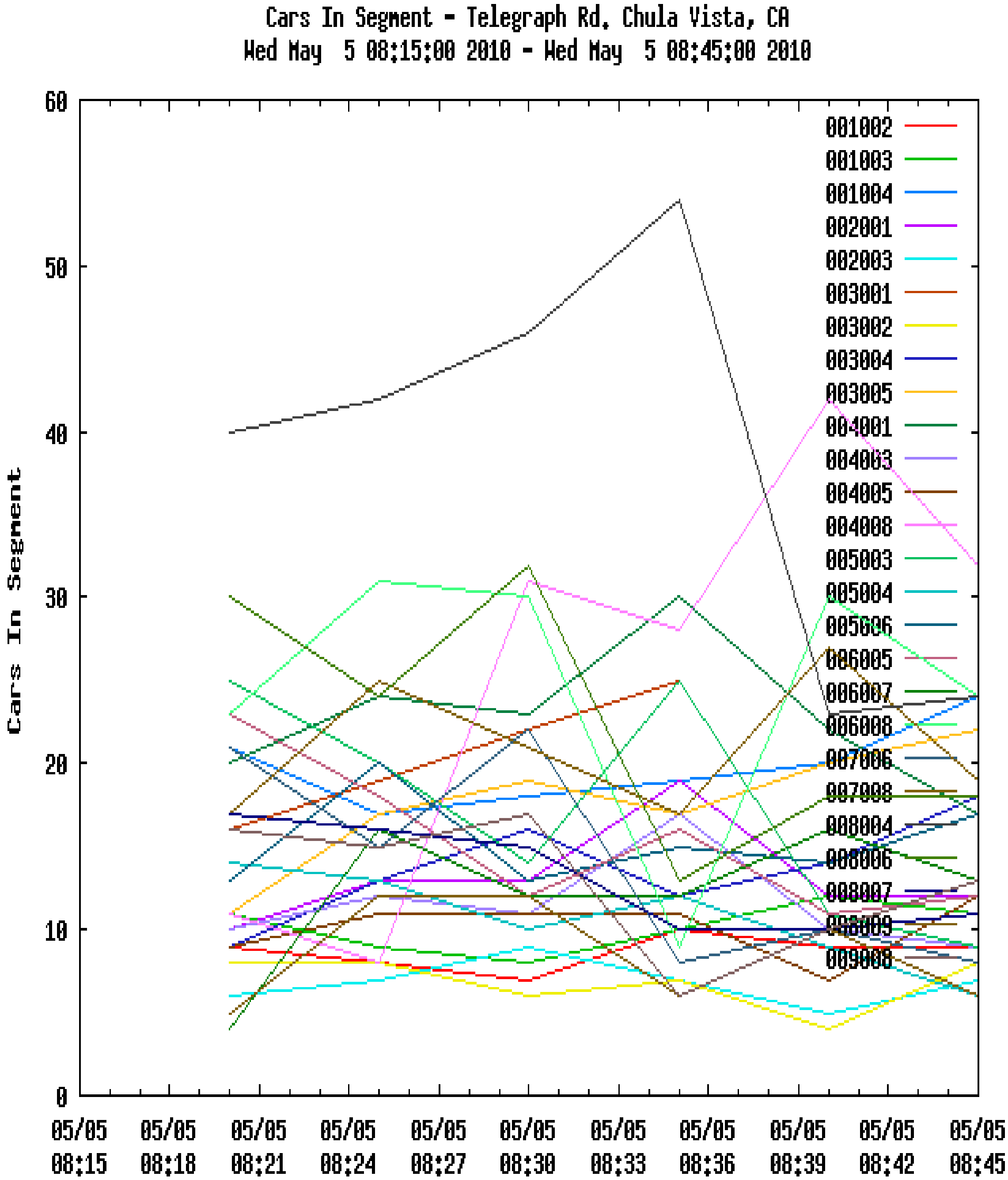


Figure 10: Car in Segments for ATTS
(Source: http://www.sensysnetworks.com/traveltime)

Other transportation data such as AADTs (major and minor roads), posted speeds, signal timing cycle lengths were provided by Chula Vista County Traffic Operations. In addition, geometric design data such as exclusive turn lanes (right and left), number of intersection legs, number of lane at intersections, access density, right and left turn lane lengths for major and minor roads are collected from Google.

4.4 Alternative Travel Time Data Collection Methods

- License Plate Recognition (LPR)

  LPR systems use the license plate number as the identifying signature. At each end A and B, a vehicle presence detector triggers a camera, which records the time and captures an image of the vehicle. Optical Character Recognition (OCR) software processes the image to produce an alphanumeric sequence, presumably the license plate number (Kavaler et al., 2009). Matching is error-prone: in one trial conducted by Florida Department of Transportation in 2006 OCR software misread 50% of the license numbers.[21]

- Electronic Toll Collection Tag Readers (ETC)

  RFID (Radio-Frequency Identification) tags for toll collection can be read and time stamped by readers placed at the two ends A and B. The matching is better than LPR because OCR errors are avoided. However, the scheme can only be used when there is a sufficient penetration rate of tags.

- Bluetooth

  Some drivers use a Bluetooth device to connect "hands-free" with their cell phone. The radio connection uses a 48-bit address unique to the device. If a

---

[21] Florida Department of Transportation. LPR Field Test Results Report, August 2006.

vehicle with Bluetooth device "on" is traversing a segment and if the device is in "discovery" mode, Bluetooth scanners located at the two ends can discover and record the time-stamped address. Matched addresses yield the device travel time. The typical Bluetooth device has a range of 10 meters (348 feet), so the scanner must operate with larger power. Unlike LPR and RFID tag readers, Bluetooth scanners do not require line of sight access to the device in the vehicle. However, an experiment conducted in Indiana (I-465) reported rates of 1.2 and 0.7 percent (Wasson et al., 2008).

- GPS Phones

  Whereas LPR, ETC tag and Bluetooth readers are fixed at locations A and B in order to sample the travel times over the link AB, GPS phones serve as mobile probes that measure travel times for the link AB only and when they happen to traverse it. GPS phones potentially provide inexpensive and ubiquitous travel time measurements (Kavaler et al., 2009). However, GPS readings may be inaccurate, especially on arterials with tall buildings.

- Time-Space/Platoon Diagram Generator (TS-PP/Draft)

  This method using a Global Positioning System (GPS) receiver, the traffic engineering software Time-Space/Platoon Progression Diagram Generator (TS-PP/Draft), and a laptop mounted in the test vehicle measures travel time, running time, distance traveled, and the type, location, duration, and cause of traffic delays along the study route.[22] The length of the road segment or the entire corridor is integrated from Geographic Intelligence System (GIS) with detailed map

---

[22] Sarasota County Public Works, Traffic Engineering and Operations. 2007 Annual Corridor Travel Time and Delay Study.

representation. Additionally, data is recorded automatically as the test vehicle traverses the study route. The driver of the test vehicle proceeds along the study route in accordance with one of the following techniques:

- Average-Car Technique: the test vehicle travels according to the driver's judgment of the average speed of the traffic stream.
- Floating-Car Technique: the driver "floats" with the traffic by attempting to safely pass as many vehicles as pass the test vehicle. The floating car technique is generally applied only on two-lane highways where passing is rare and the number of passings can be counted and balanced easily (Roess et al., 2010).
- Maximum-Car Technique: the test vehicle is driven at the posted speed limit unless impeded by actual traffic conditions or safety considerations.

The disadvantages of this method are: the travel time is collected for only one car and the driving technique used cannot be verified.

Among the arterial travel time data collection methods outlined above, the ATTS (Arterial Travel Time System) from Sensys Networks appears to be the only one deployed that provides an accurate real-time estimate of the travel time distribution and traffic counts. Additionally, the mean travel time as well as its standard deviation or 80th percentile is estimated.

Chapter 5- Statistical Results and Discussion

5.1 Travel Time and Reliable Travel Time Data Analysis

Travel time data for each segment in this research is presented in the Appendices. Figures 11, 12, 13, and 14 illustrate the travel times for the different roadway segments and different peak time periods. It is obvious that travel time is influenced by the time of the day and other factors such as roadway geometry and regulation, traffic management and control, and driving direction. For instance, in the morning peak period, the average travel time is 97.89 seconds when driving westbound on segment # 9008, whereas 52.97 seconds are needed to cross the same segment when driving eastbound. In addition, 106.72 seconds are needed to cross segment # 7008 in the morning peak period, whereas 152.57 seconds are needed in the afternoon peak period.

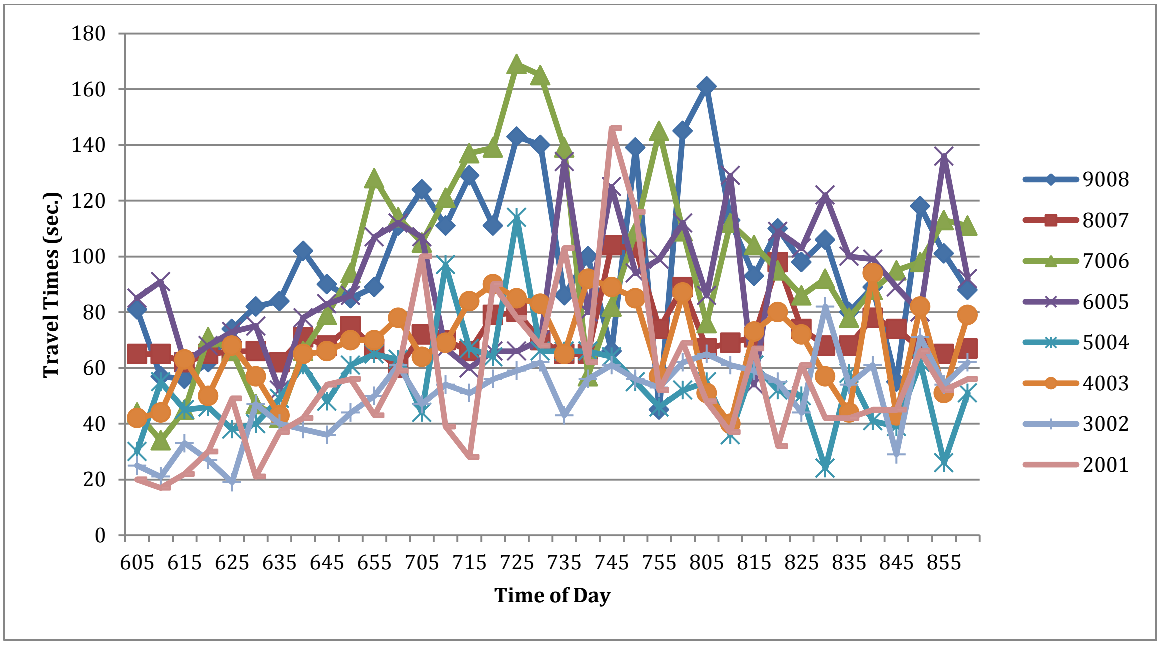


Figure 11: Travel Times for Morning Peak Time Periods (Driving West)

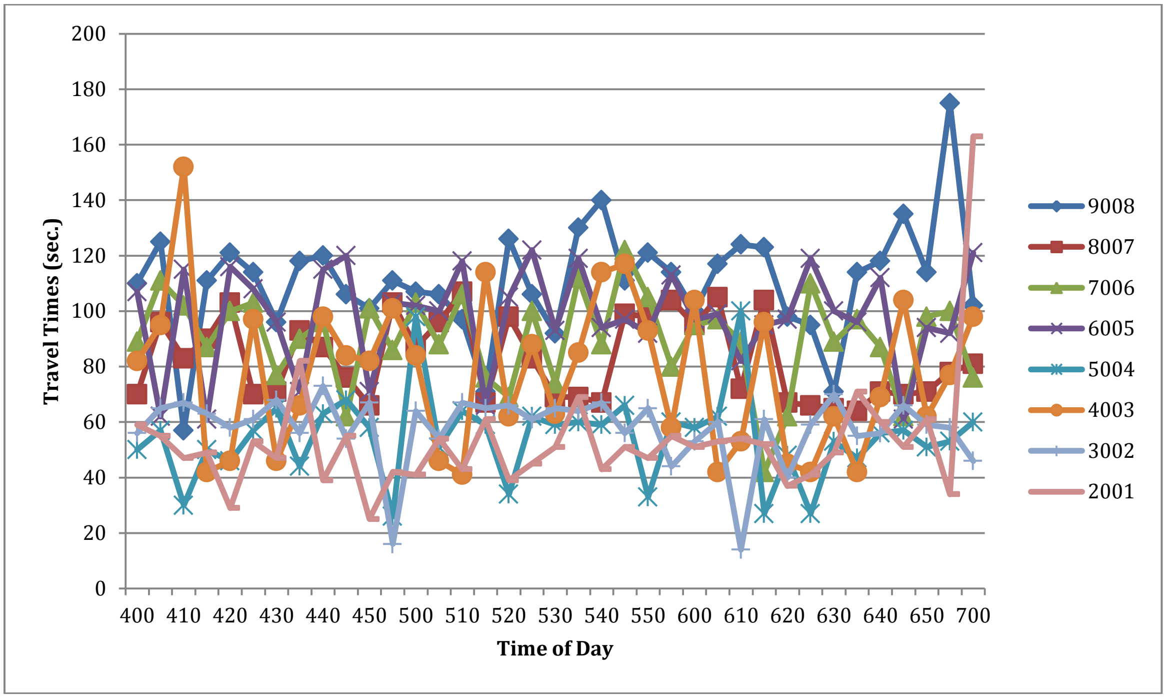


Figure 12: Travel Times for Afternoon Peak Time Periods (Driving West)

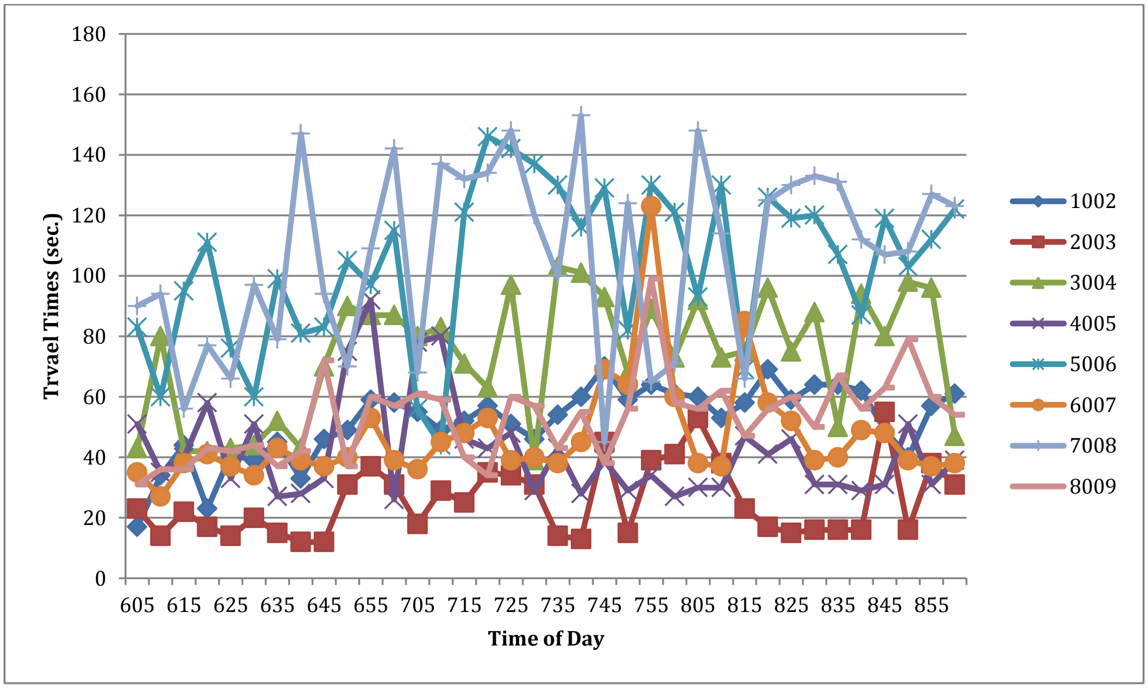


Figure 13: Travel Times for Morning Peak Time Periods (Driving East)

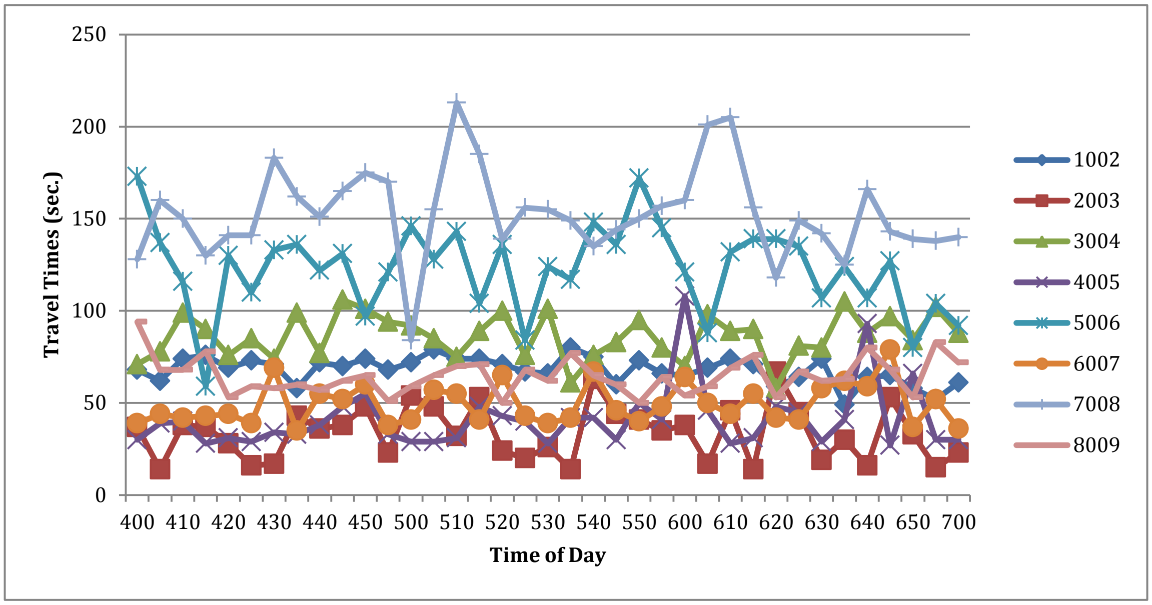


Figure 14: Travel Times for Afternoon Peak Time Periods (Driving East)

By applying the assumption made in the previous chapter that roadway segments are reliable when travel time threshold is equal to or lowers than the buffer time added to the average travel time, the buffer time is established to determine the travel time reliability thresholds for the different segments. In addition, we assume 15th percentile travel time as the free flow travel time. From the 3,503 travel times selected, 3,361 are considered reliable and this number varies by segment based on their attributes. Figures 15 thru 30 show the average travel times (AAT), travel time reliability thresholds (TTRT), and the buffer times (BT) for the road segments. Table 3 summarizes these figures by illustrating that the buffer index is not only related to segment length but also to other traffic and geometric characteristics. For instance, driving westbound, segment # 002001 is 65.01% (96.79-31.78) more congested than segment #003002 whereas they have only 0.05 mile length differential. On the contrary, segment # 002003 is 68.85% (94.87-26.02) more congested than segment # 001002 when driving eastbound.

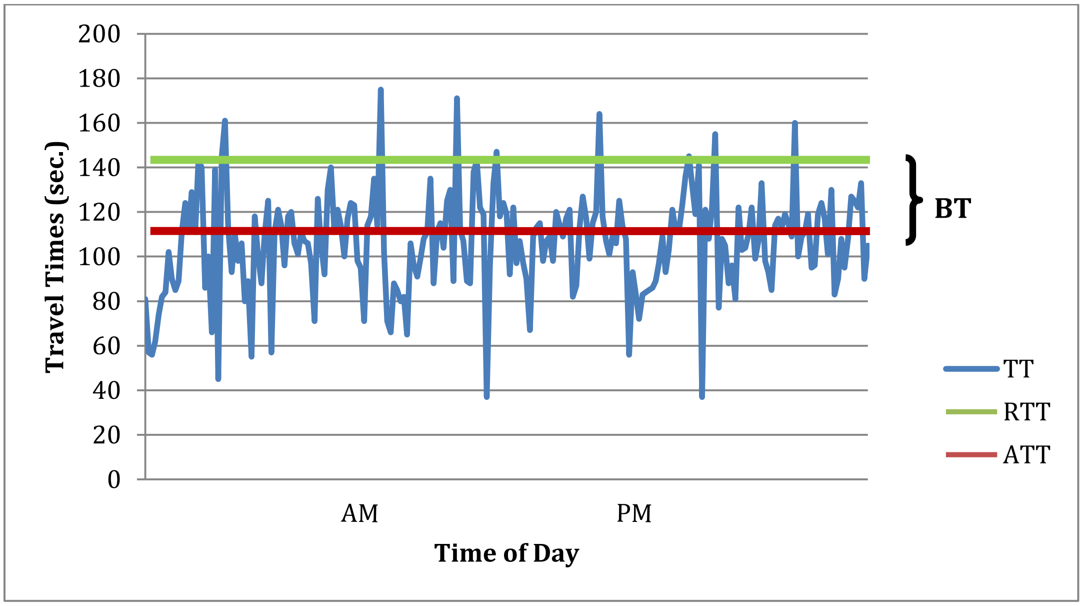


Figure 15: Buffer Time (sec.) for Segment # 9008 for Peak Periods (Driving West)

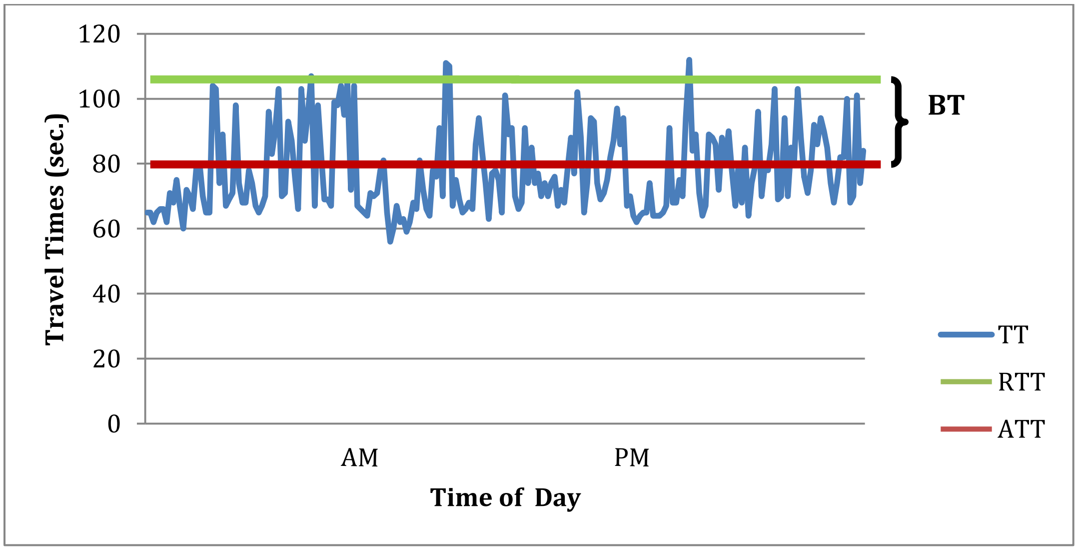


Figure 16: Buffer Time (sec.) for Segment # 8007 for Peak Periods (Driving West)

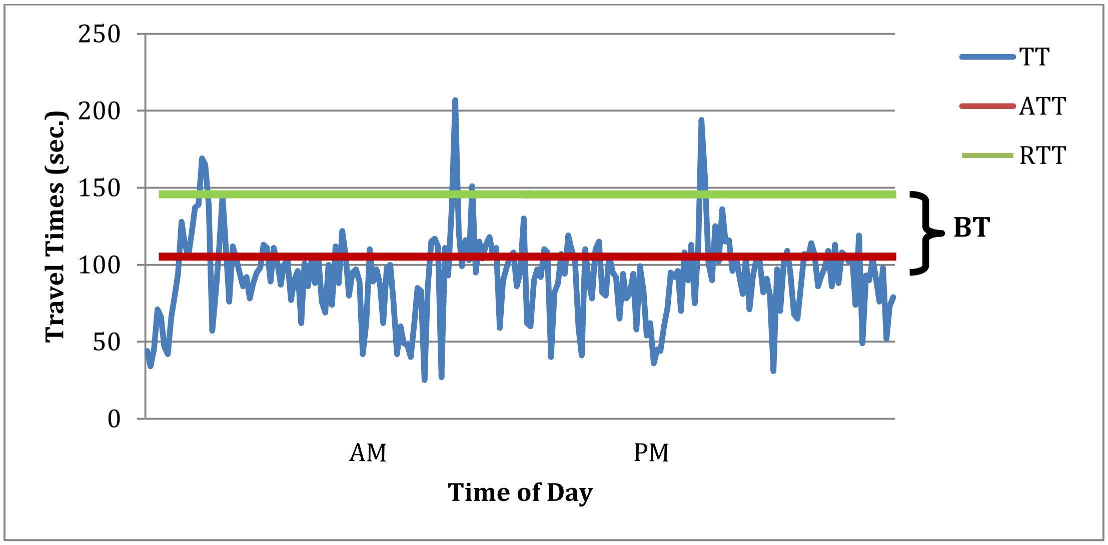


Figure 17: Buffer Time (sec.) for Segment # 7006 for Peak Periods (Driving West)

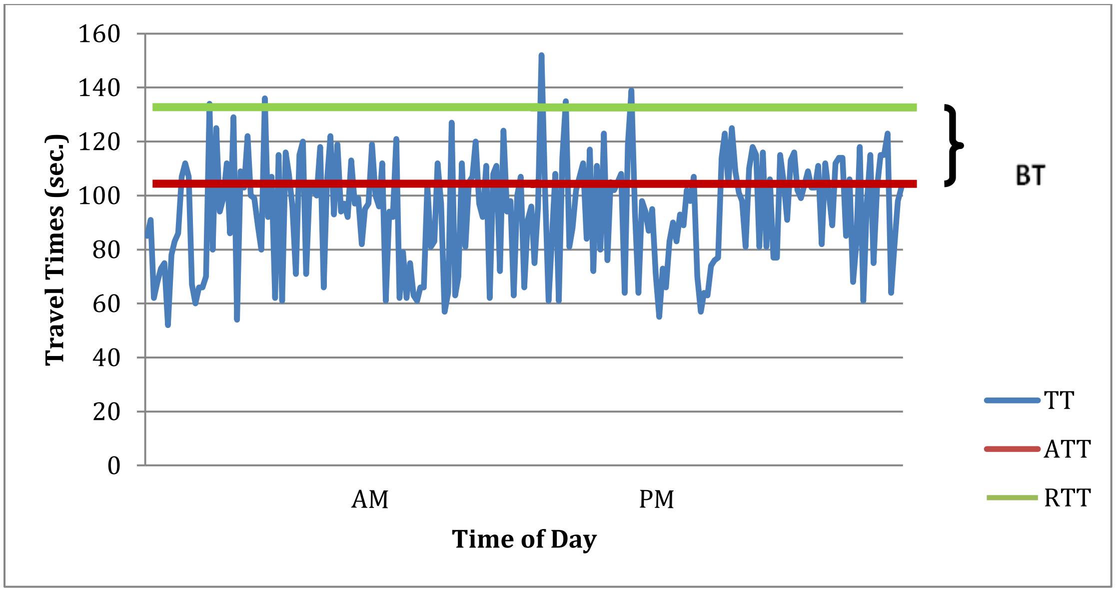


Figure 18: Buffer Time (sec.) for Segment # 6005 for Peak Periods (Driving West)

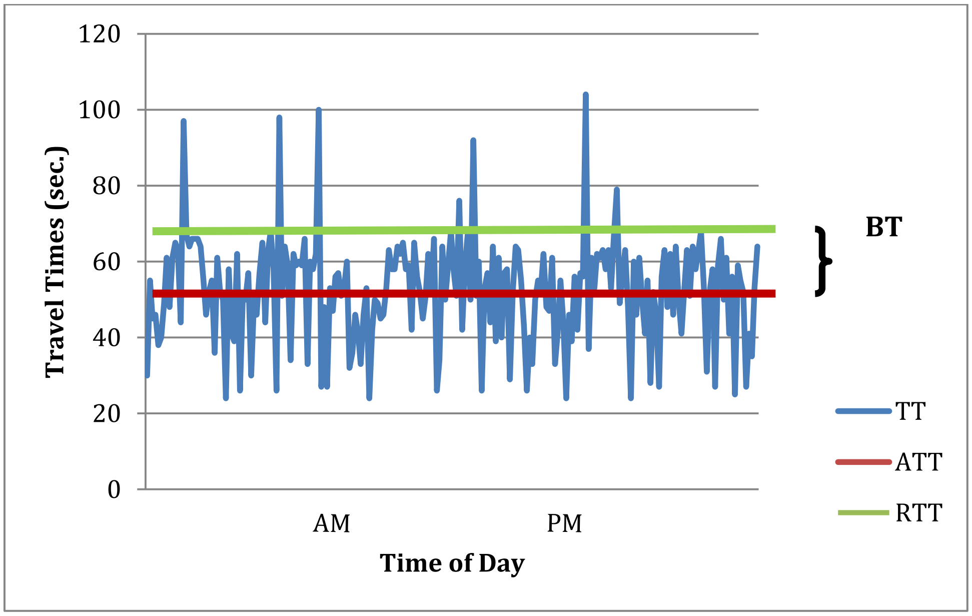


Figure 19: Buffer Time (sec.) for Segment # 5004 for Peak Periods (Driving West)

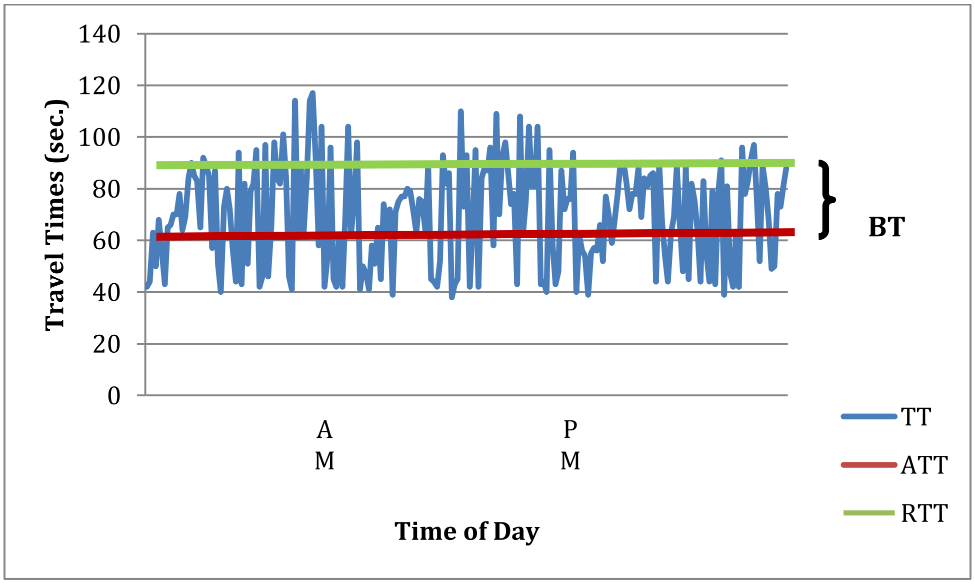


Figure 20: Buffer Time (sec.) for Segment # 4003 for Peak Periods (Driving West)

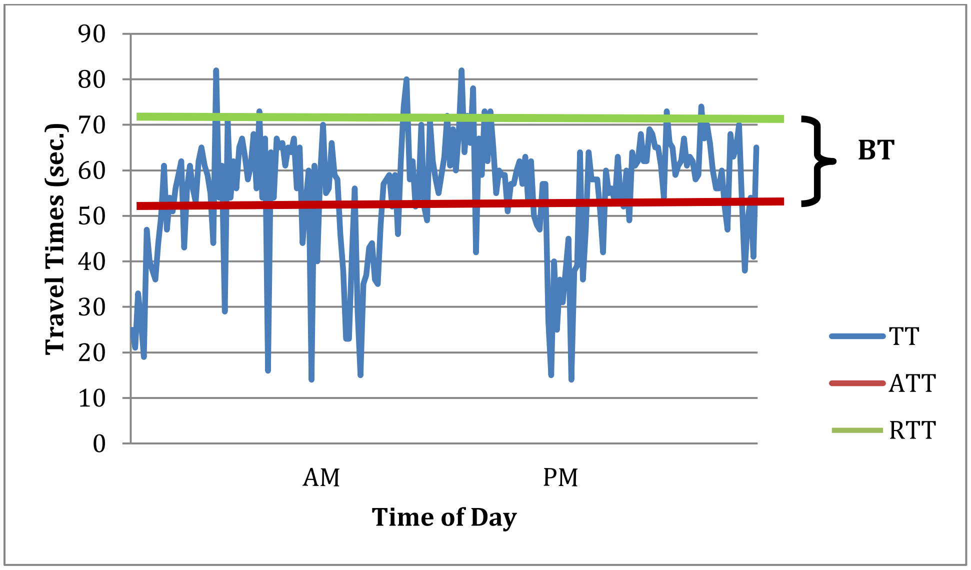


Figure 21: Buffer Time (sec.) for Segment # 3002 for Peak Periods (Driving West)

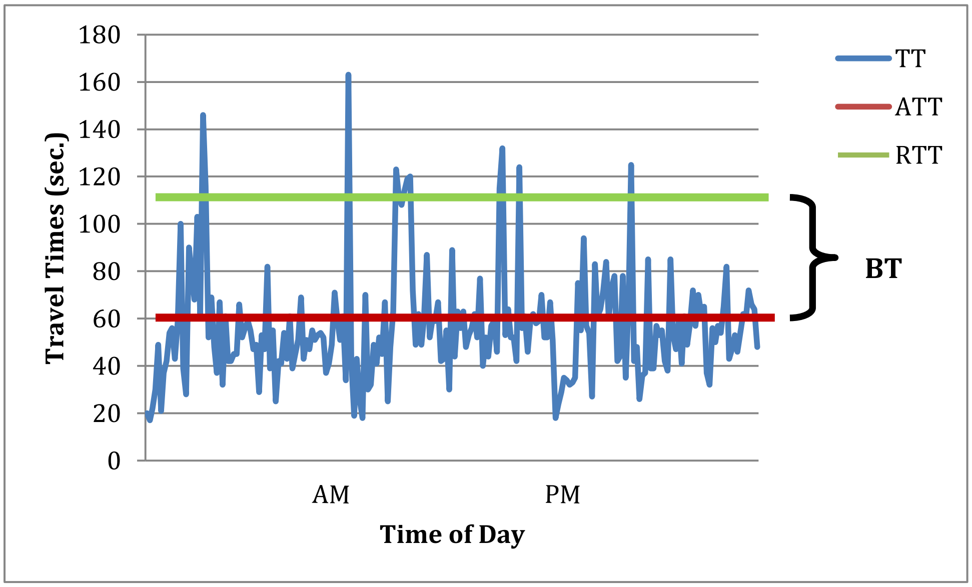


Figure 22: Buffer Time (sec.) for Segment # 2001 for Peak Periods (Driving West)

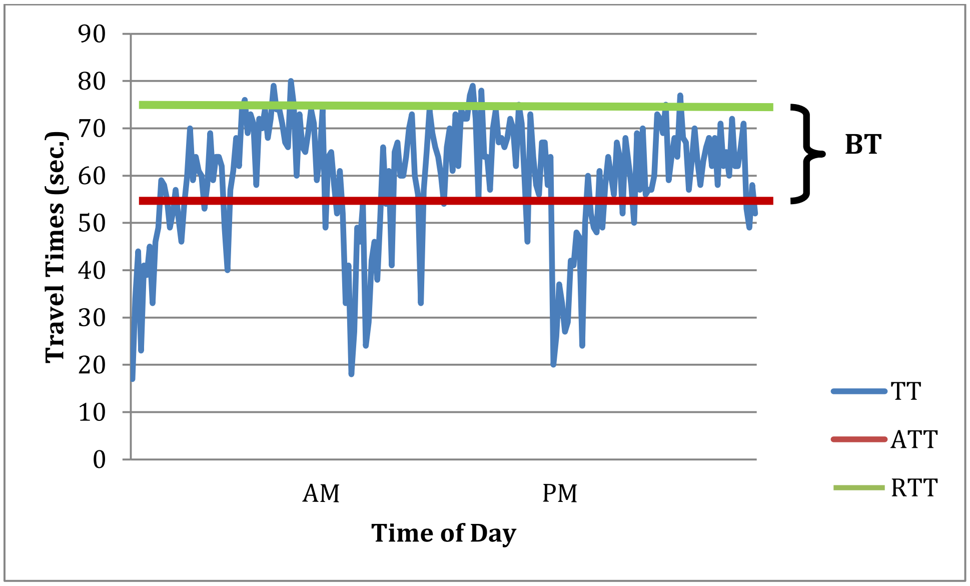


Figure 23: Buffer Time (sec.) for Segment # 1002 for Peak Periods (Driving East)

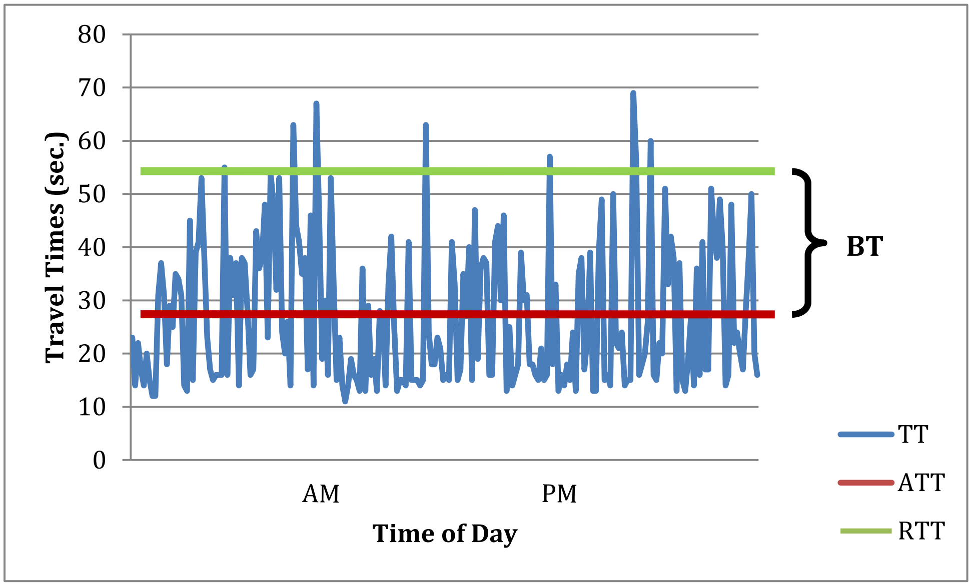


Figure 24: Buffer Time (sec.) for Segment # 2003 for Peak Periods (Driving East)

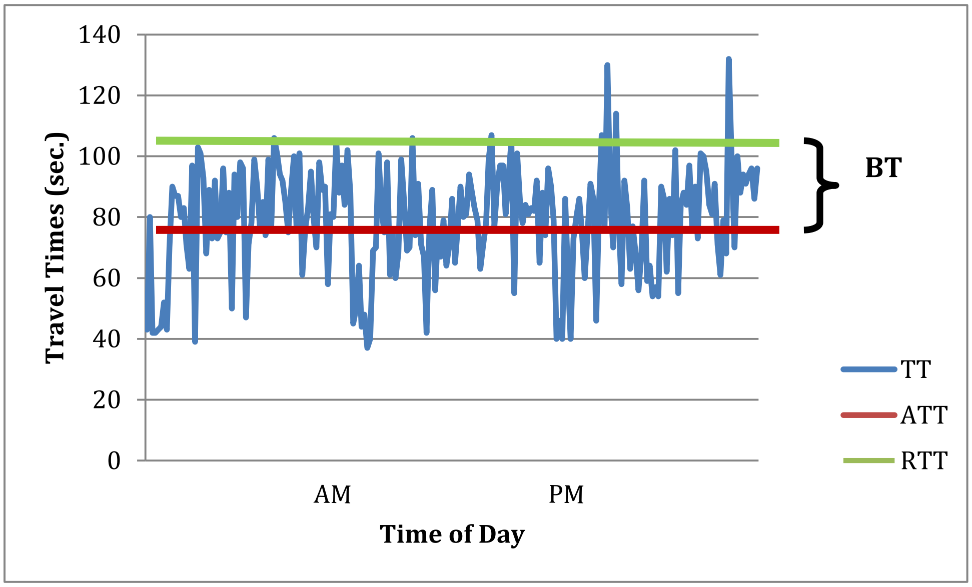


Figure 25: Buffer Time (sec.) for Segment # 3004 for Peak Periods (Driving East)

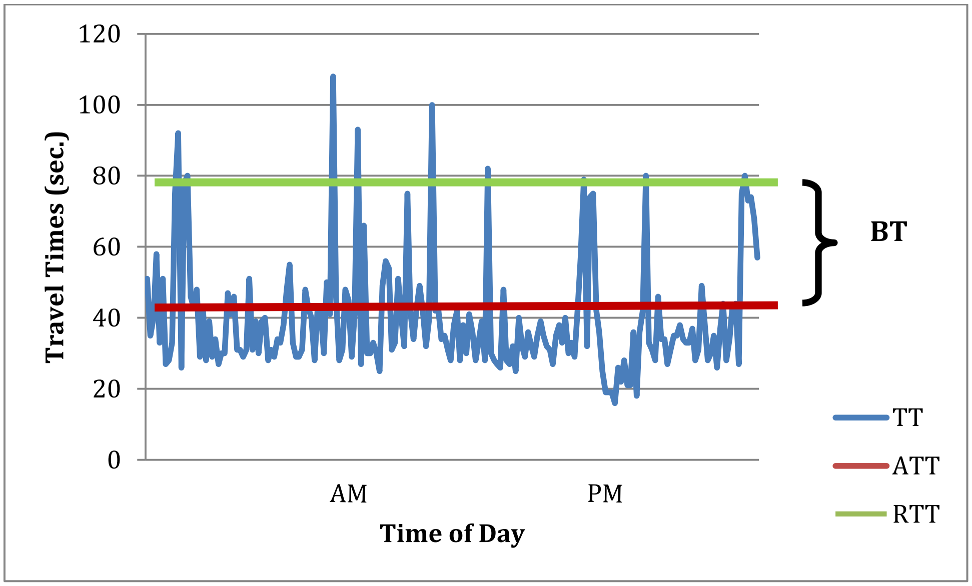


Figure 26: Buffer Time (sec.) for Segment # 4005 for Peak Periods (Driving East)

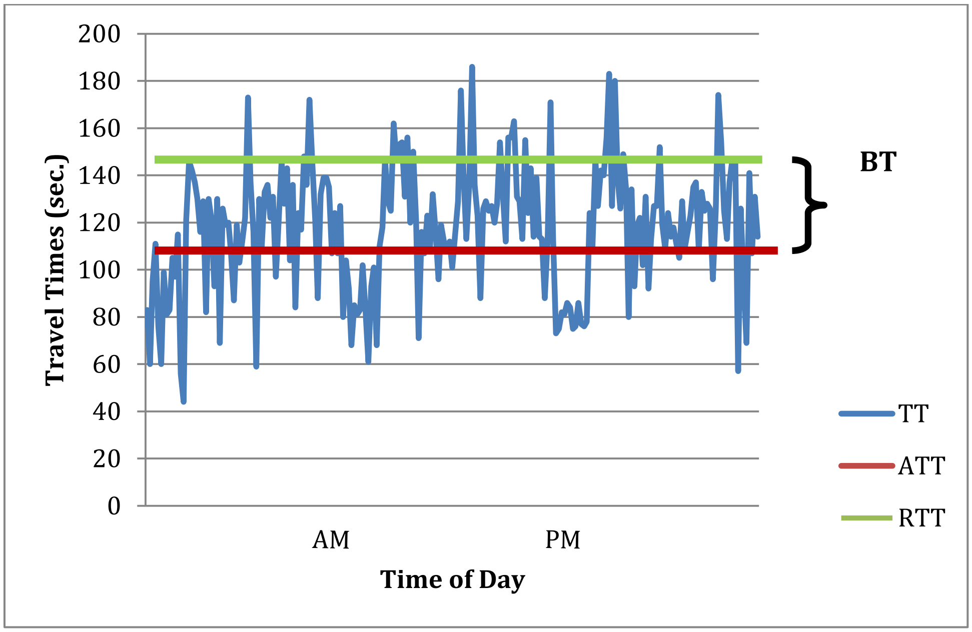


Figure 27: Buffer Time (sec.) for Segment # 5006 for Peak Periods (Driving East)

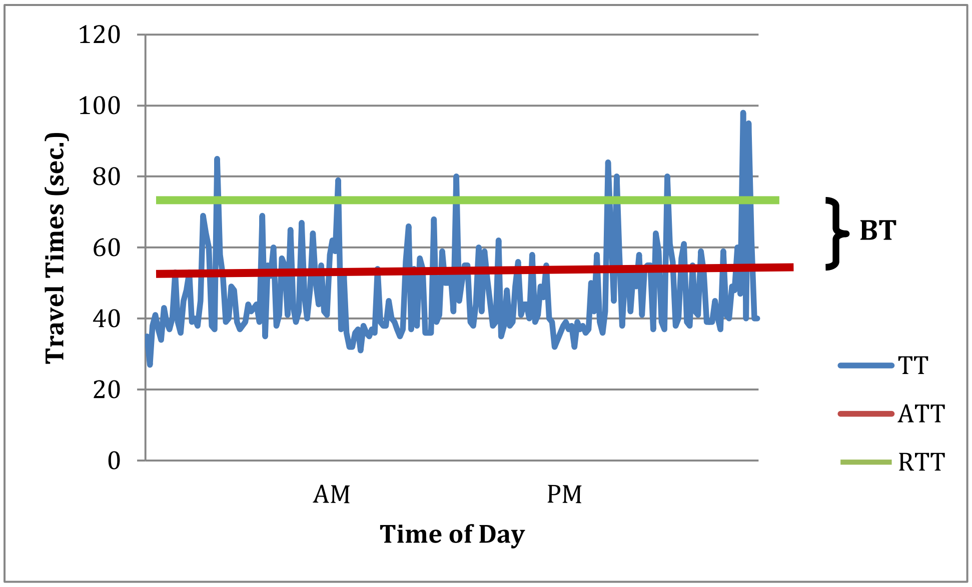


Figure 28: Buffer Time (sec.) for Segment # 6007 for Peak Periods (Driving East)

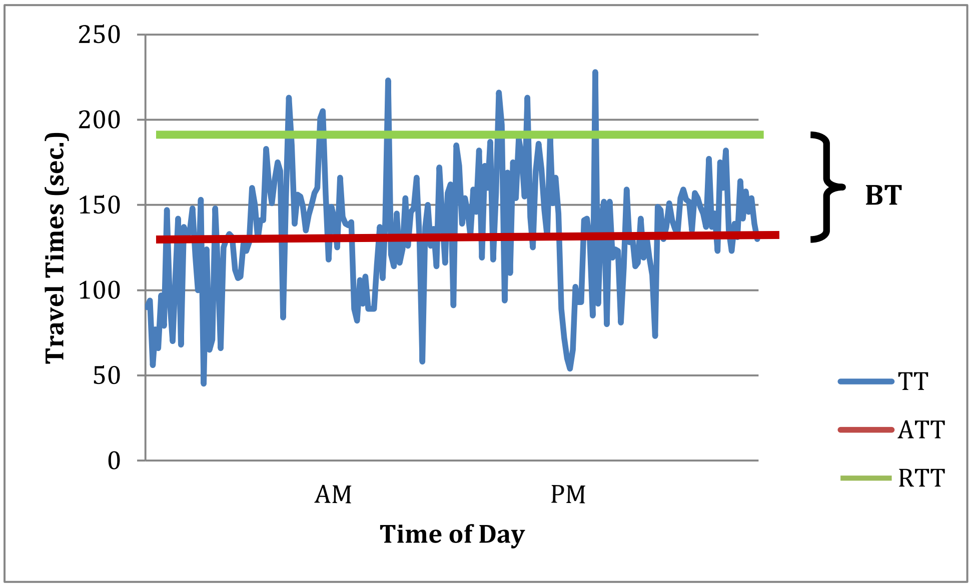


Figure 29: Buffer Time (sec.) for Segment # 7008 for Peak Periods (Driving East)

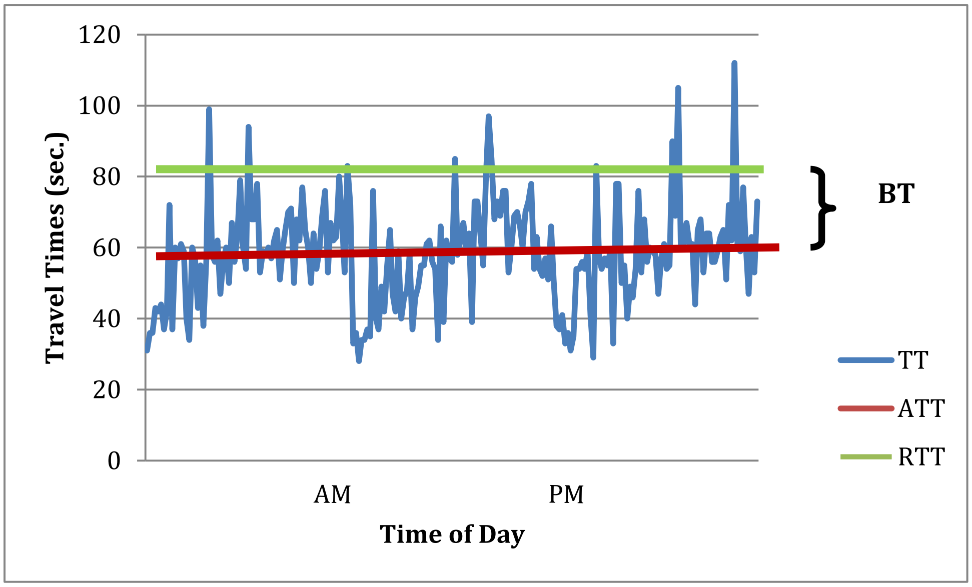


Figure 30: Buffer Time (sec.) for Segment # 8009 for Peak Periods (Driving East):

Table 3: Travel Time Reliability Thresholds and Buffer Times for the Segments

Segment Number	**Length (mil)**	**Average Travel Time (Sec)**	**Buffer Index (%.)**	**Buffer Times (sec.)**	**TT Reliability Thresholds (sec)**	**Driving Direction**
009008	0.46	106	33.02	35.05	141.2	Westward
008007	0.90	77.37	33.19	25.62	103	
007006	0.47	92.16	47.67	44.44	136.6	
006005	0.75	93.77	31.16	29.22	123	
005004	0.30	52.55	27.67	14.54	67.10	
004003	0.54	70.46	47.59	33.53	104	
003002	0.15	55.39	31.78	17.60	73	
002001	0.20	56.55	96.79	54.74	111.3	
001002	0.20	59.51	26.02	15.48	75	Eastward
002003	0.15	27.19	94.87	25.80	53	
003004	0.54	78.69	29.73	23.40	102.1	
004005	0.30	37.97	97.48	37.02	75	
005006	0.75	117.44	32.82	38.55	156	
006007	0.47	47.06	44.68	21.03	68.1	
007008	0.90	132.95	39.96	53.14	186.1	
008009	0.46	58.75	41.68	24.42	83	

5.2 Single Linear Regression and Correlation Analysis

After illustrating the travel time variation due to influencing factors, the single linear regression and correlation analysis is performed by computing equation [4] to determine how correlated the influencing factors are.

$$r_{xy} = \frac{n\sum XY - \sum X \sum Y}{\sqrt{\left[n\sum X^2 - \left(\sum X\right)^2\right] * \left[n\sum Y^2 - \left(\sum Y\right)^2\right]}} \qquad [4]$$

For instance, Arterial Segment Length and Reliable Travel times X_4, Y are denoted respectively.

n=3361; ΣX=1585.89; ΣY=237345; ΣXY=129371.59; $(\Sigma X)^2$=2515047;

$(\Sigma Y)^2$=56332649025; ΣX^2=947.6455 and ΣY^2=20437449.

Equation [4] becomes:

$$r_{xy}= \frac{(3361*129371.59)-(1585.89*237345)}{\sqrt{[(3361*947.6455)-2515047]}*\sqrt{[(3361*20437449)-56332649025]}}$$

r_{xy} **=** 0.642**,** which means that Reliable Travel Time and Arterial Segment Length are correlated.

The same process is applied to the other correlations and the results are listed in Table 4.

Table 4: Single Linear Regression and Correlation among Factors

	Y	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16
Y	1.000	0.310	-0.035	-0.382	0.642	-0.241	-0.388	-0.119	0.102	0.040	-0.383	0.515	0.387	0.549	-0.170	0.470	0.586
X1	0.310	1.000	0.012	(-0.818)	0.575	-0.184	(-0.908)	0.354	0.003	0.491	(-0.817)	0.404	0.162	-0.035	-0.151	0.575	0.259
X2	-0.035	0.012	1.000	-0.012	0.000	0.012	-0.001	0.008	-0.017	0.010	-0.012	0.015	-0.008	0.011	0.187	0.017	0.004
X3	-0.382	(-0.818)	-0.012	1.000	-0.639	0.341	(0.693)	-0.400	-0.018	-0.474	(1.000)	-0.471	-0.088	-0.124	0.208	-0.492	-0.339
X4	0.642	0.575	0.000	-0.639	1.000	-0.536	(-0.685)	-0.082	0.078	-0.068	-0.639	0.232	0.387	0.320	-0.128	0.248	0.594
X5	-0.241	-0.184	0.012	0.341	-0.536	1.000	0.375	0.259	-0.147	0.157	0.341	0.124	0.127	-0.053	0.050	0.028	-0.229
X6	-0.388	(-0.908)	-0.001	(0.693)	(-0.685)	0.375	1.000	-0.205	-0.323	-0.408	(0.692)	-0.221	-0.422	-0.052	0.156	-0.429	-0.319
X7	-0.119	0.354	0.008	-0.400	-0.082	0.259	-0.205	1.000	0.000	0.140	-0.399	0.087	-0.059	-0.063	0.027	0.252	0.257
X8	0.102	0.003	-0.017	-0.018	0.078	-0.147	-0.323	0.000	1.000	0.351	-0.018	-0.228	(0.758)	0.203	-0.161	-0.163	-0.014
X9	0.040	0.491	0.010	-0.474	-0.068	0.157	-0.408	0.140	0.351	1.000	-0.473	0.432	0.310	-0.050	-0.210	0.331	-0.298
X10	-0.383	(-0.817)	-0.012	(1.000)	-0.639	0.341	(0.692)	-0.399	-0.018	-0.473	1.000	-0.471	-0.087	-0.124	0.208	-0.492	-0.339
X11	0.515	0.404	0.015	-0.471	0.232	0.124	-0.221	0.087	-0.228	0.432	-0.471	1.000	0.040	0.299	-0.101	(0.805)	0.297
X12	0.387	0.162	-0.008	-0.088	0.387	0.127	-0.422	-0.059	(0.758)	0.310	-0.087	0.040	1.000	0.353	-0.148	-0.018	0.207
X13	0.549	-0.035	0.011	-0.124	0.320	-0.053	-0.052	-0.063	0.203	-0.050	-0.124	0.299	0.353	1.000	-0.067	0.339	0.664
X14	-0.170	-0.151	0.187	0.208	-0.128	0.050	0.156	0.027	-0.161	-0.210	0.208	-0.101	-0.148	-0.067	1.000	-0.076	0.004
X15	0.470	0.575	0.017	-0.492	0.248	0.028	-0.429	0.252	-0.163	0.331	-0.492	0.805	-0.018	0.339	-0.076	1.000	0.373
X16	0.586	0.259	0.004	-0.339	0.594	-0.229	-0.319	0.257	-0.014	-0.298	-0.339	0.297	0.207	0.664	0.004	0.373	1.000

Notes: The values in parentheses represent the highly correlated variables where Y(Reliable Travel Times); X_1(Posted Speed); X_2(Signal Timing Cycle Length); X_3(AADT major road); X_4(Arterial Segment Length); X_5(Number of Intersection Legs); X_6(Access Density); X_7(Exclusive RT minor road); X_8(Exclusive RT major road); X_9 (Number of Lanes @ Intersection), X_{10}(VPHPL); X_{11}(Left Turn Lane Major); X_{12}(AADT minor road); X_{13}(Right Turn Lane major); X_{14}(Time of Day); X_{15}(Left Turn Lane minor); X_{16}(Right Turn Lane minor).

Table 4 illustrates the high correlation among some factors (independent variables) and, in particular cases, one variable provides no additional information over and above its perfectly correlated counterpart. For instance, posted speed is highly correlated to AADT on major road, access density, and VPHPL.

Also, as shown on Table 5 (next page), based on the single linear regression analysis, the first three significant factors to travel time reliability on urban arterials are from the geometric design category. This order of significance means that the functional layout of travel lanes curb ramps, crosswalks, turning lanes, number of intersection legs, and bike lanes in both horizontal and vertical dimensions have a profound influence on roadway safety and operational performance for all road users. Additionally, the table illustrates that Arterial Segment Length (X_4) is the most contributing factor to travel time reliability (Y), whereas Signal Timing Cycle Length (X_2) is the least contributing factor. However, the final order of significance for the factors to urban travel time reliability will be determined after the multiple linear regression analysis, which will be performed in the next paragraph.

Table 5: Independent Variables (Factors) by Order of Significance

Category	**Variable**	**Description**	**Order of Significance**
Geometric Design	X_4	Arterial Length	1
	X_5	Number of Intersection Legs	11
	X_6	Access Density	6
	X_7	Exclusive R/T Minor Road	13
	X_8	Exclusive R/T Major Road	14
	X_9	Number Lanes @ Intersection	15
	X_{11}	Left Turn Lane Major Road	4
	X13	Right Turn Lane Major Road	3
	X_{15}	Left Turn Lane Minor Road	5
	X_{16}	Right Turn Lane Minor Road	2
Traffic Design	X_1	Posted Speed	10
	X_2	Signal Timing Cycle Length	16
	X_3	AADT Major Road	8
	X_{10}	VPHPL	9
	X_{12}	AADT Minor Road	7
Temporal	X_{14}	Time of Day	12

5.3 Multiple Linear Regression Analysis

Equation [5] is computed along with selected influencing factors to generate the linear relationship between reliable travel time and the influencing factors. The description of the selected independent variables is illustrated in table 6 and the summary output is displayed afterward.

Table 6: Description of Selected Independent Variables

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	0	0
	X_5	Number of Intersection Legs	Continuous (Count)	8.49E+12	0.111316
	X_6	Access Density	Continuous	-1.9E+12	0.111316
	X_7	Exclusive R/T Minor Road	Continuous (Count)	-1.3E+12	0.111316
	X_8	Exclusive R/T Major Road	Continuous (Count)	-3.3E+12	0.111316
	X_9	Number Lanes @ Intersection	Continuous (Count)	1.11E+11	0.111316
	X_{11}	L/T Lane Major Road	Continuous (Count)	0.060041	1.7E-22
	X_{13}	R/T Lane Major Road	Continuous (Count)	0.033256	6.03E-07
Traffic Design	X_1	Posted Speed	Continuous	-4E+12	0.111316
	X_2	Signal Timing Cycle Length	Continuous	-0.16441	0.012711
	X_3	AADT Major Road	Continuous	-4.5E+08	0.111316
	X_{10}	VPHPL	Continuous	0	0
	X_{12}	AADT Minor Road	Continuous	-4.5E+08	0.111316
Geometric Design	X_{16}	R/T Lane Minor	Continuous	0.0239	6.25E-06
	X_{15}	L/T Lane Minor	Continuous	0.02388	1.68E-08
Temporal	X_{14}	Time of Day	Dummy	-4.69658	1.94E-11

Table 7: Summary Output # 1

Multiple R	0.825
R-Square	0.681
Adjusted R-Square	0.679
Standard Error	18.720
Observations	3362

Table 8: ANOVA # 1 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	16	2508728	156795	511.29
Residuals	3347	1173025	350.47	
Total	3363	3681753		

As shown in Table 6, Left Turn Lane on Major Road (X_{11}), Right Turn Lane on Major Road (X_{13}), Time of Day (X_{14}), Left Turn Lane on Minor Road (X_{15}), and Right Turn Lane on Minor Road (X_{16}) five of the selected independent variables, are significant to the model. The nonsignificance of the other variables does not mean they do not influence travel time reliability on the corridor rather their influences are explained by other factors to which they are highly correlated.

The equation for the normal multiple regression is:

$Y=2.04\ X10^{14}+0.060X_{11}-4.05X10^{08}X_{12}+0.03X_{13}+4.69X_{14}+0.02X_{15}+0.02X_{16}+\varepsilon$ [5].

In addition, Table 7 shows 68.1% of the variance in travel time reliability is explained by the selected independent variables. The other 31.9% remains unexplained.

To capture more significant variables into the model forward stepwise regression will be performed with the most significant variable from the single linear regression analysis. First, X_4 (Arterial Length), the most significant variable from the single linear regression will be considered.

Table 9: First Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficient**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	87.25	0

Table 10: Summary Output # 2

Multiple R	0.642
R-Square	0.412
Adjusted R-Square	0.412
Standard Error	25.368
Observations	3362

Table 11: ANOVA # 2 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	1	1519458	1519458	2361.091
Residuals	3360	2162296	643.54	
Total	3361	3681753		

Table 10 shows that X_4 explains 41.3% of the observed data.

The equation resulting from this first regression is the following:

$Y= 29.43+87.25X_4 + \varepsilon$ [6].

The second regression will be performed with X_4 and X_6 the second most significant variable based on the single linear regression. The result is illustrated in Table 12.

Table 12: Second Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	61.824	1E-168
	X_{16}	Right Turn Lane Minor	Continuous	0.06	1.05E-86

Table 13: Summary Output # 3

Multiple R	0.690
R-Square	0.477
Adjusted R-Square	0.476
Standard Error	23.94
Observations	3362

Table 14: ANOVA # 3 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	2	1756247	878123.6	1531.886
Residuals	3359	1925506	573.2379	
Total	3361	3681753		

Table 12 and Table 13 show the two selected variables X_4 (Segment Length) and X_{16} (Left Turn Lane Minor Road) are significant and explain 47.7% of the observed data. The following equation is from the second regression.

$$Y=31.986+61.824X_4+0.06X_{16}+\varepsilon \qquad [7]$$

The third stepwise regression will be performed with X_4, X_{16}, and X_{13}

Table 15: Third Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	67.36	2.03E-168
	X_{16}	Right Turn Lane Minor	Continuous	0.010	0.002
	X_{13}	Right Turn Lane Major	Continuous	0.10	7.03E-105

Table 16: Summary Output # 4

Multiple R	0.738
R-Square	0.545
Adjusted R-Square	0.545
Standard Error	22.31
Observations	3362

Table 17: ANOVA # 4 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	3	2009283	669760.6	1344.75
Residuals	3358	1672470	498.05	
Total	3361	3681753		

Table 15 and Table 16 show three selected variables X_4 (segment Length), X_{16} (Left Turn Lane Minor Road), and X_{13} (Right Turn Lane Major Road) are significant and explain 54.5% of the observed data. The following equation is from the third regression.

$$Y=29.287+67.360X_4+0.01X_{16}+0.10X_{13} + \varepsilon \qquad [8]$$

The fourth stepwise regression will be performed with X_4 (Arterial Length), X_{16} (Left Turn Lane Minor Road), X_{13} (Right Turn Lane Major Road), and X_2 (Signal Timing Cycle Length).

Table 18: Fourth Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	67.343	6.3E-219
	X_{16}	Right Turn Lane Minor	Continuous	0.011	0.002
	X_{13}	Right Turn Lane Major	Continuous	0.107	1.8E-105
Traffic Design	X_2	Signal Timing Cycle Length	Continuous	-0.258	0.0007

Table 19: Summary Output # 5

Multiple R	0.738
R-Square	0.547
Adjusted R-Square	0.546
Standard Error	22.28
Observations	3362

Table 20: ANOVA # 5 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	4	2014917	503729.3	1014.508
Residuals	3357	1666836	496.52	
Total	3361	3681753		

Table 18 and Table 19 show the four selected variables X_4 (segment Length), X_{16} (Left Turn Lane Minor Road), X_{13} (Right Turn Lane Major Road), and X_2 (Signal Timing Cycle Length) are significant and explain 54.72% of the observed data. Additionally, all the signs are correct.

The following equation is from the fourth regression.

$$Y=64.323+67.348X_4+0.011X_{16}+0.10X_{13}-0.258X_2+\varepsilon \qquad [9]$$

The fifth stepwise regression will be performed with X_4 (Arterial Length), X_{16} (Left Turn Lane Minor Road), X_{13} (Right Turn Lane Major Road), X_2 (Signal Timing Cycle Length), and X_1 (Posted Speed).

Table 21: Fifth Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	64.113	3.1E-150
	X_{16}	Right Turn Lane Minor	Continuous	0.010	0.004
	X_{13}	Right Turn Lane Major	Continuous	0.110	1.1E-104
Traffic Design	X_2	Signal Timing Cycle Length	Continuous	-0.262	0.0006
	X_1	Posted Speed	Continuous	0.361	0.009

Table 22: Summary Output # 6

Multiple R	0.740
R-Square	0.548
Adjusted R-Square	0.547
Standard Error	22.28
Observations	3362

Table 23: ANOVA # 6 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	5	2018284	403656.6	814.3655
Residuals	3356	1663469	495.670	
Total	3361	3681753		

Table 21 and Table 22 show the five selected variables X_4 (segment Length), X_{16} (Left Turn Lane Minor Road), X_{13}(Right Turn Lane Major Road), X_2 (Signal Timing Cycle Length), and X_1(Posted Speed) are significant and explain 54.8% of the observed data. Additionally, all the signs are correct.

The following equation is from the fifth regression.

$$Y=49.043+64.113X_4+0.010X_{16}+0.110X_{13}-0.262X_2+0.361X_1+\varepsilon \qquad [10].$$

The sixth stepwise regression will be performed with X_4 (Arterial Length), X_{16} (Left Turn Lane Minor Road), X_{13} (Right Turn Lane Major Road), X_2(Signal Timing Cycle Length), X_1(Posted Speed), and X_{15}(Left Turn Lane Minor Road).

Table 24: Sixth Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	88.180	6.1E-265
	X_{16}	Right Turn Lane Minor	Continuous	-0.002	0.523
	X_{13}	Right Turn Lane Major	Continuous	0.060	1.1E-34
	X_{15}	Left Turn Lane Minor Road	Continuous	0.057	2.3E-139
Traffic Design	X_2	Signal Timing Cycle Length	Continuous	-0.269	0.0001
	X_1	Posted Speed	Continuous	-2.711.	3.36E-54

Table 25: Summary Output # 7

Multiple R	0.791
R-Square	0.625
Adjusted R-Square	0.625
Standard Error	20.266
Observations	3362

Table 26: ANOVA # 7 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	6	2303754	383959	934.821
Residuals	3355	1377999	410.73	
Total	3361	3681753		

Table 24 and Table 25 show five of the selected variables X_4 (segment Length), X_{13}(Right Turn Lane Major Road), X_2 (Signal Timing Cycle Length), X_{15}(Left Turn Lane

Minor), and X_1(Posted Speed) are significant and explain 62.57% of the observed data. X_{16} (Right Turn Lane Minor Road) is not significant and will be removed from the regression and replaced by another variable.

Another stepwise regression will be performed with X_4 (Arterial Length), X_{13} (Right Turn Lane Major Road), X_2(Signal Timing Cycle Length), X_1(Posted Speed), X_{15}(Left Turn Lane Minor Road), and X_3(AADT Major Road).

Table 27: Seventh Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	89.543	3.1 E-360
	X_{13}	Right Turn Lane Major	Continuous	0.060	4.15E-45
Traffic Design	X_{15}	Left Turn Lane Minor	Continuous	0.057	2.4E-142
	X_2	Signal Timing Cycle Length	Continuous	-0.267	0.0001
	X_3	AADT Major	Continuous	0.0002	0.0007
	X_1	Posted Speed	Continuous	-2.278	2.37E-26

Table 28: Summary Output # 8

Multiple R	0.791
R-Square	0.626
Adjusted R-Square	0.626
Standard Error	20.233
Observations	3362

Table 29: ANOVA # 8 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	6	2308295	384715.9	939.75
Residuals	3355	1373459	409.37	
Total	3361	3681753		

Table 27 and Table 28 show the six selected variables X_4 (segment Length), X_{13} (Right Turn Lane Major Road), X_2 (Signal Timing Cycle Length), X_1 (Posted Speed), X_{15} (Left Turn Lane Minor), and X_3 (AADT Major Road) are significant and explain 62.6% of the observed data.

The following equation is from the seventh regression.

$Y=141.55+89.54X_4+0.060X_{13}-0.267X_2-2.278X_1+0.05\,X_{15}+0.0002\,X_3+\varepsilon$ [11].

Another stepwise regression will be performed with X_4 (Arterial Length), X_{13} (Right Turn Lane Major Road), X_2(Signal Timing Cycle Length), X_1(Posted Speed), X_{15} (Left Turn Lane Minor Road), X_3 (AADT Major Road), and X_{10} (VPHPL).

Table 30: Eighth Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	97.840	6.3E-289
	X_{13}	Right Turn Lane Major	Continuous	0.058	1.24E-42
	X_{15}	Left Turn Lane Minor	Continuous	0.059	9.8E-151
Traffic Design	X_2	Signal Timing Cycle Length	Continuous	-0.262	0.0001
	X_3	AADT Major	Continuous	-0.213	8.86E-13
	X_1	Posted Speed	Continuous	-3.430	2.09E-37
	X_{10}	VPHPL	Continuous	15.416	8.35E-13

Table 31: Summary Output # 9

Multiple R	0.791
R-Square	0.632
Adjusted R-Square	0.631
Standard Error	20.082
Observations	3362

Table 32: ANOVA # 9 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	7	2329104	332729.2	825.02
Residuals	3355	1352649	403.294	
Total	3361	3681753		

Table 30 and Table 31 show the seven selected variables X_4 (segment Length), X_{13}(Right Turn Lane Major Road), X_2 (Signal Timing Cycle Length), X_1 (Posted Speed), X_{15} (Left Turn Lane Minor), X_3 (AADT Major Road), and X_{10} (VPHPL) are significant and explain 63.26% of the observed data. However, despite the increased R^2 the regression will be rejected because X_3 has the wrong sign, which could be caused by X_{10} Therefore X_{10} will be replaced by X_5 (Number of Intersection Legs) in the next regression.

Table 33: Ninth Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	95.862	6.53E-38
	X_{13}	Right Turn Lane Major	Continuous	0.055	1.2E-142
	X_{15}	Left Turn Lane Minor	Continuous	0.057	1.24E-07
	X_5	Number of Intersection Legs	Continuous	4.801	9.72E-05
Traffic Design	X_2	Signal Timing Cycle Length	Continuous	-0.271	0.030
	X_3	AADT Major	Continuous	0.0001	2.26E-31
	X_1	Posted Speed	Continuous	-2.584	2.09E-37

Table 34: Summary Output # 10

Multiple R	0.793
R-Square	0.63
Adjusted R-Square	0.629
Standard Error	20.152
Observations	3362

Table 35: ANOVA # 10 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	7	2319699	331385.5	816.022
Residuals	3354	1362055	406.098	
Total	3361	3681753		

Table 33 and Table 34 show the seven selected variables X_4 (segment Length), X_{13}(Right Turn Lane Major Road), X_2 (Signal Timing Cycle Length), X_1 (Posted Speed),

X_{15} (Left Turn Lane Minor), X_3 (AADT Major Road), and X_5 (Number of Intersection Legs) are significant and explain 63% of the observed data.

The following equation is from the ninth regression.

$$Y=141.237+95.862X_4+0.055X_{13}-0.271X_2-2.584X_1+0.057X_{15}+0.0001X_3 +4.801X_5 + \varepsilon \quad [12]$$

The above significant variables along with X_9(Number Lanes at Intersection) will considered for the next regression.

Table 36: Tenth Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
	X_4	Arterial Length	Continuous	119.097	2.3E-253
Geometric Design	X_9	Number Lanes at Intersection	Continuous	1.429	5.06E-53
	X_{13}	Right Turn Lane Major	Continuous	0.042	2.99E-23
	X_{15}	Left Turn Lane Minor Road	Continuous	0.061	2.4E-172
	X_5	Number of Intersection Legs	Continuous	3.639	3.49E-05
Traffic Design	X_2	Signal Timing Cycle Length	Continuous	-0.267	7.75E-05
	X_3	AADT Major	Continuous	0.0006	3.84E-16
	X_1	Posted Speed	Continuous	-3.821	2.02E-61

Table 37: Summary Output # 11

Multiple R	0.809
R-Square	0.655
Adjusted R-Square	0.654
Standard Error	19.460
Observations	3362

Table 38: ANOVA # 11 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	8	2411872	301485	796.03
Residuals	3353	1269881	378.72	
Total	3361	3681753		

Table 36 and Table 37 show the eight selected variables X_4 (segment Length), X_{13}(Right Turn Lane Major Road), X_2 (Signal Timing Cycle Length), X_1(Posted Speed), X_{15}(Left Turn Lane Minor), X_3 (AADT Major Road), X_5(Number of Intersection Legs), and X_9(Number Lanes at Intersection) are significant and explain 65.50% of the observed data.

The following equation is from the tenth regression.

$$Y=132.44+119.097X_4+0.042X_{13}-0.267X_2-3.821X_1+0.061X_{15}+0.0006X_3+3.639X_5+1.429X_9+\varepsilon \quad [13].$$

The above significant variables along with X_6(Access Density) will be considered for the next regression.

Table 39: Eleventh Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	116.454	2.33E-238
	X_9	Number Lanes at Intersection	Continuous	1.338	1.511E-34
	X_{13}	Right Turn Lane Major	Continuous	0.039	3.95E-19
	X_{15}	Left Turn Lane Minor Road	Continuous	0.063	1.55E-161

Table 39 (Continued)

Geometric Design	X_5	Number of Intersection Legs	Continuous	4.747	2.207E-05
	X_6	Access Density	Continuous	-0.329	0.108
Traffic Design	X_2	Signal Timing Cycle Length	Continuous	-0.263	8.77E-05
	X_3	AADT Major	Continuous	0.0005	8.53E-06
	X_1	Posted Speed	Continuous	-4.555	8.66E-19

Table 40: Summary Output # 12

Multiple R	0.809
R-Square	0.655
Adjusted R-Square	0.654
Standard Error	19.460
Observations	3362

Table 41: ANOVA # 12 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	9	2412846	268095	708.208
Residuals	3352	1268987	378.55	
Total	3361	3681753		

Table 39 and Table 40 show eight of the selected variables X_4 (segment Length), X_{13}(Right Turn Lane Major Road), X_2 (Signal Timing Cycle Length), X_1(Posted Speed), X_{15}(Left Turn Lane Minor), X_3 (AADT Major Road), X_5(Number of Intersection Legs), and X_9(Number Lanes at Intersection) are significant and explain 65.50% of the observed data. X_6(Access Density) is not significant and will be removed and replaced by X_7 (Exclusive Right Turn Minor Road) in the next regression.

Table 42: Twelfth Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	124.90	2.7E-233
	X_9	Number Lanes at Intersection	Continuous	1.161	7.95E-44
	X_{13}	Right Turn Lane Major	Continuous	0.039	3.35E-20
	X_{15}	Left Turn Lane Minor Road	Continuous	0.063	9.3E-172
	X_5	Number of Intersection Legs	Continuous	2.595	0.0068
	X_7	Exclusive Right Turn Minor Road	Continuous	2.983	0.006
Traffic Design	X_2	Signal Timing Cycle Length	Continuous	-0.263	8.78E-05
	X_3	AADT Major	Continuous	0.0008	2.11E-15
	X_1	Posted Speed	Continuous	-4.093	5.19E-61

Table 43: Summary Output # 13

Multiple R	0.809
R-Square	0.655
Adjusted R-Square	0.654
Standard Error	19.442
Observations	3362

Table 44: ANOVA # 13 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	9	2414629	268292.2	709.729
Residuals	3352	1267124	378.020	
Total	3361	3681753		

Table 42 and Table 43 show the nine selected variables X_4 (Segment Length), X_{13}(Right Turn Lane Major Road), X_2 (Signal Timing Cycle Length), X_1(Posted Speed), X_{15}(Left Turn Lane Minor), X_3 (AADT Major Road), X_5(Number of Intersection Legs), X_9(Number Lanes at Intersection), and X_7 (Exclusive Right Turn Minor Road) are significant and explain 65.58% of the observed data.

The following equation is from the twelfth regression.

$$Y=127.693+124.90X_4+0.039X_{13}-0.263X_2-4.093X_1+0.063X_{15}+0.0008X_3 +2.595X_5+1.161X_9+2.983X_7+\varepsilon \qquad [14].$$

The above significant variables along with X_{11}(Left Turn Lane Major Road) will be considered for the next regression.

Table 45: Thirteenth Linear Regression Analysis

Category	Variable	Description	Type	Coefficients	P-Value
Geometric Design	X_4	Arterial Length	Continuous	111.19	4.6E-183
	X_9	Number Lanes at Intersection	Continuous	1.166	7.86E-23
	X_{13}	Right Turn Lane Major	Continuous	0.056	1.11E-36
	X_{15}	Left Turn Lane Minor Road	Continuous	0.025	2.32E-12
	X_5	Number of Intersection Legs	Continuous	-3.551	0.0007
	X_7	Exclusive Right Turn Minor Road	Continuous	6.409	9.22E-09
	X_{11}	Left Turn Lane Major Road	Continuous	0.055	1.02E-35
Traffic Design	X_2	Signal Timing Cycle Length	Continuous	-0.262	6.38E-05
	X_3	AADT Major	Continuous	0.001	2.23E-33
	X_1	Posted Speed	Continuous	-2.105	7.45E-15

Table 46: Summary Output # 14

Multiple R	0.819
R-Square	0.674
Adjusted R-Square	0.673
Standard Error	18.99
Observations	3362

Table 47: ANOVA # 14 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	10	2472144	247214.4	684.862
Residuals	3351	1209609	360.969	
Total	3361	3681753		

Table 45 and Table 46 show the ten selected variables X_4 (Segment Length), X_{13}(Right Turn Lane Major Road), X_2 (Signal Timing Cycle Length), X_1(Posted Speed), X_{15}(Left Turn Lane Minor), X_3 (AADT Major Road), X_5(Number of Intersection Legs), X_9(Number Lanes at Intersection), X_7 (Exclusive Right Turn Minor Road), and X_{11}(Left Turn Lane Major Road) are significant and explain 67.4% of the observed data. The other 32.86% remains unexplained, which could be attributed to driving behavior, driver group age, traffic congestion, month of the year, location of activities, nonrecurrent events (e.g., weather conditions, roadway construction) because most urban travel time information databases do not currently connect travel time data to the special events or construction maintenance activity.

The following equation is from the thirteenth regression.

$$Y=36.198+111.192X_4+0.056X_{13}-0.262X_2-2.105X_1+0.025X_{15}+0.001X_3$$

$$-3.551X_5+1.166X_9+6.409X_7+0.055X_{11}+\varepsilon \qquad [15].$$

The above significant variables along with X_6(Access Density) will be considered for the next regression.

Table 48: Fourteenth Linear Regression Analysis

Category	**Variable**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	785.581	0.820
	X_9	Number Lanes at Intersection	Continuous	-0.054	1.74E-32
	X_{13}	Right Turn Lane Major	Continuous	0.056	6.27E-08
	X_{15}	Left Turn Lane Minor Road	Continuous	0.020	0.0006
	X_5	Number of Intersection Legs	Continuous	-1.354	6.57E-43
	X_7	Exclusive Right Turn Minor Road	Continuous	0.068	6.97E-09
	X_6	Access Density	Continuous	-2.064	8.88E-05
Traffic Design	X_2	Signal Timing Cycle Length	Continuous	-0.627	0.739
	X_3	AADT Major	Continuous	0.001	5.1E-17
	X_1	Posted Speed	Continuous	-5.267	7.45E-15

Table 49: Summary Output # 15

Multiple R	0.821
R-Square	0.671
Adjusted R-Square	0.670
Standard Error	19.20
Observations	3362

Table 50: ANOVA # 15 (Analysis of Variance)

	df	**SS**	**MS**	**F**
Regression	11	2484197	225836.1	631.74
Residuals	3350	1197557	357.47	
Total	3361	3681753		

Table 48 and Table 49 show eight of the ten selected variables X_{13}(Right Turn Lane Major Road), X_1(Posted Speed), X_3(AADT Major Road), X_9(Number Lanes at Intersection), X_7(Exclusive Right Turn Minor Road), X_{15}(Left Turn Lane Minor), X_5(Number of Intersection Legs), and X_6(Access Density) are significant and explain 67.1% of the observed data. However, X_4 (Segment Length) and X_2 (Signal Timing Cycle Length) are not significant and will be removed from the model. Therefore equation 15 remains the equation of the model.

For the multiple correlation analysis, the order of significance for the factors will be generated from the correlation among the significant variables and the travel time thresholds (reliable).

As shown on Table 51 based on the multiple linear regression analysis, the first four significant factors to travel time reliability on urban arterials are from the geometric design and traffic categories. This order of significance means travel time reliability on urban arterials depends on the capacity (the maximum theoretical traffic flow rate that a highway section is capable of accommodating under a given set of environmental, highway, and traffic conditions) of factors such as the number of lanes, lane width, effectiveness of traffic control systems, frequency and duration of traffic incidents, number of intersecting legs, and traffic volumes from the cross streets. In addition, Table 51 reveals the order of significance for the factors is different in the multiple linear regression analysis compared to the single linear regression analysis. This difference can explain a great deal of variability in the response variable. Therefore, interactions in the regression model will be performed in the next section. Adding interaction terms to the regression model can greatly expand understanding of the relationship among variables in the model and allows testing additional hypotheses (Grace-Martin, 2000).

Table 51: Independent Variables (Factors) by Order of Significance

Category	**Variable**	**Description**	**Order of Significance**
Geometric Design	X_4	Arterial Length	1
	X_5	Number of Intersection Legs	7
	X_7	Exclusive R/T Minor Road	8
	X_9	Number Lanes @ Intersection	9
	X_{11}	Left Turn Lane Major Road	3
	X_{13}	Right Turn Lane Major Road	2
	X_{15}	Left Turn Lane Minor Road	4
Traffic Design	X_1	Posted Speed	6
	X_2	Signal Timing Cycle Length	10
	X_3	AADT Major Road	5

5.4 Interaction Effects in the Regression Model

Interactions in regression models represent a combined or synergistic effect of two or more variables (Washington et al., 2003). The presence of a significant interaction indicates that the effect of one predictor variable on the response variable is different at different values of the other predictor variable. (Grace-Martin, 2000). Part of the multiple linear regression is the ability to estimate and test interaction effects when the predictor variables are either categorical or continuous (Stevens, 2010).

In a linear model representing the variation in a dependent variable Y as a linear function of several explanatory variables, interaction between two explanatory variables X_1 and X_2 can be represented by their product, which is the variable created by multiplying them together (Burrill, 2011).

Algebraically such a model is represented by the following equation:

$$Y = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 + \ldots\ldots + \varepsilon \qquad [16].$$

When X_1 and X_2 are category systems, equation [16] describes a two-way analysis of variance model; when X_1 and X_2 are (quasi-) continuous variables.

Adding an interaction term to a model drastically changes the interpretation of all the coefficients. In the multiple linear regression contexts, an interaction implies a change in the slope (of the regression of Yon X_1) from one value of X_2 to another value of X_2 or, equivalently, a change in the slope of the regression of Y on X_2 for different values of $X_{1.}$ (Burrill, 2011).

The interaction between X_3 (AADT Major Road) and X_2 (Signal Timing Cycle Length) is considered and their product added as a new variable to equation [5]. The summary output is displayed in Table 53.

Table 52: Description of Variables Including Interaction X_3X_2

Category	**Variables**	**Description**	**Type**	**Coefficients**	**P-Value**
Geometric Design	X_4	Arterial Length	Continuous	111.208	4.8E-184
	X_5	Number of Intersection Legs	Continuous (Count)	-3.557	0.00057
	X_7	Exclusive R/T Minor Road	Continuous (Count)	6.414	9.04E-09
	X_9	# Lanes @ Intersection	Continuous (Count)	1.116	7.65E-23
	X_{11}	Left Turn Lane Major Road	Continuous (Count)	0.055	1.02E-35
	X_{13}	Left Turn Lane Minor Road	Continuous (Count)	-41.3362	0.0003844
	X_{15}	Left Turn Lane Minor Road	Continuous	0.056	1.02E-35
Traffic	X_1	Posted Speed	Continuous	-2.105	7.42E-14
	X_2	Signal Timing Cycle Length	Continuous	-0.441	0.269
	X_3	AADT Major Road	Continuous	0.0008	0.380
N/A	X_3X_2	N/A	Continuous	3.28E-0	0.649

Table 53: Summary Output # 16

Multiple R	0.819
R Square	0.671
Adjusted R Square	0.670
Standard Error	19.00
Observations	3362

Table 54: ANOVA # 16 (Analysis of Variance)

	df	**SS**	**MS**
Regression	11	2472218	224447.1
Residual	3350	1209535	361.055
Total	3361	3681753	

The following equation is generated from the first interaction

$$Y=-60.373 -2.105X_1-0.441X_2+0.0008X_3+111.208X_4-3.557X_5+6.413X_7++1.165X_9 +0.055X_{11}+0.0008X_{13}+0.025X_{15}+3.28E\text{-}6X_3X_6 \qquad [17].$$

As shown in Table 52 three variables X_2 (Signal Timing Cycle Length), X_3(AADT Major Road) and the product variable X_2X_3 are not significant to the model and will be removed from [5], which will lead to the same 10 significant factors to the model. Therefore, the variable X_2X_3, resulting from the interaction between X_2 and X_3, has no significant contributions to the previous equation.

In conclusion, the interaction analysis did not explain any variation in the response variable. Therefore, equation [15] remains the multiple linear regression equation for the model.

5.5 Model Validation

In practice, the models are generally used for predictive purposes. Good fitness of data calibration does not guarantee the accuracy of future predictions. Performing validation, which requires large datasets, increases the confidence in prediction ability of a model. Unfortunately, large datasets are not always available due to high costs associated with data collection and relatively short time devoted to the studies. The validation process establishes the credibility of the model by demonstrating its ability to replicate actual traffic patterns. Validating the model requires comparing travel time estimated by the model to observed travel time on the roadway. Validation is typically an iterative process linked to calibration. If the analyst finds that the model output and the independent data are in acceptable agreement, the model can be considered validated (Pedersen & Sandahl, 1982).

Reasonableness checks and sensibility checks are normally two types of validation checks that include steps such as the comparison of rates and checking of the total regional values and logic tests. The analyst evaluates the models in terms of acceptable levels of errors, ability to perform according to theoretical and logical expectations, and consistency of model results with the assumptions used in generating the results (Wegmann & Everett, 2008).

Sensibility checks are tests that check the responses to the transportation system and socioeconomic or political changes. Sensibility is often expressed as the elasticity of the variable.

In any accuracy check errors associated with the ground counts need to be taken into account. These errors are due to equipment malfunction, the inappropriate use of daily and seasonal factors to estimate AADT, and the absence of good classification data to correct axle count to vehicles.

To validate the model, reliable travel time data collected for two different weeks are incorporated into the linear regression equation of the model and the outputs are compared to the estimated reliable travel times**.**

For instance, consider segment # 9008 and its attributes as illustrated in Table 55.

Table 55: Attributes of Segment # 9008

Y	**X_1**	**X_2**	**X_3**	**X_4**	**X_5**	**X_7**	**X_9**	**X_{11}**	**X_{13}**	**X_{15}**
89	50	72	4550	0.46	4	1	35	632	2	1

Equation [15] becomes:

36.198-2.105*50-0.262*140+0.001*45508+111.192*0.46-3.551*4+6.409*1

+1.166*35+0.055*600+0.056*248+0.025*560=84.82, which is 4.18 (89-84.82) seconds lower than the reliable travel time on the roadway.

The same process is applied to the seven other segments and the results are illustrated in Figures 31 and 32.

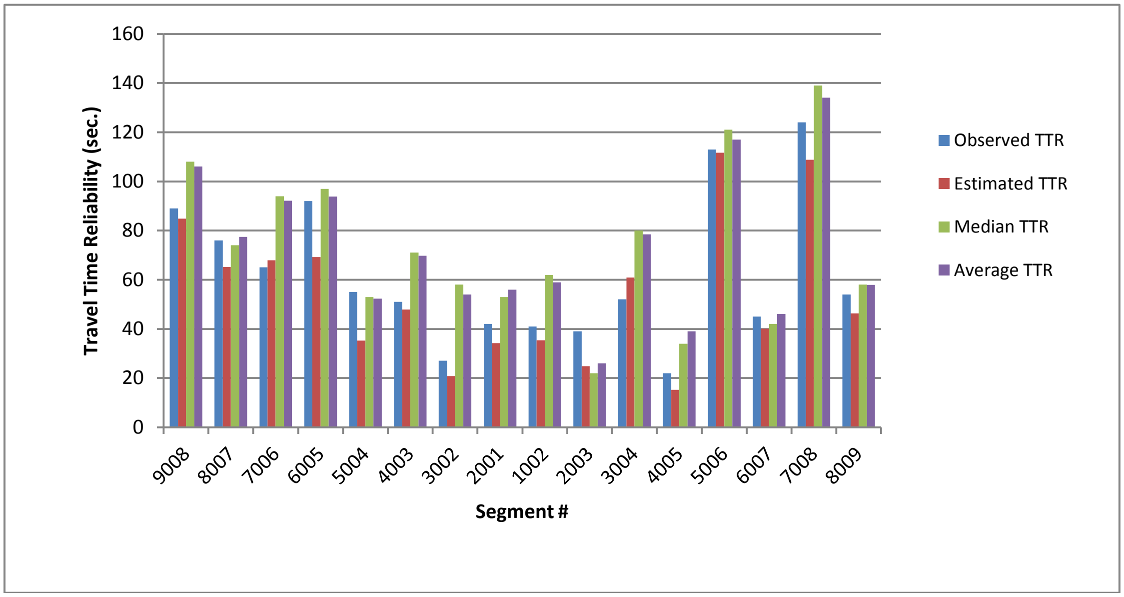


Figure 31: Travel Times Reliability Comparison for the Segments between Observed and Estimated Data

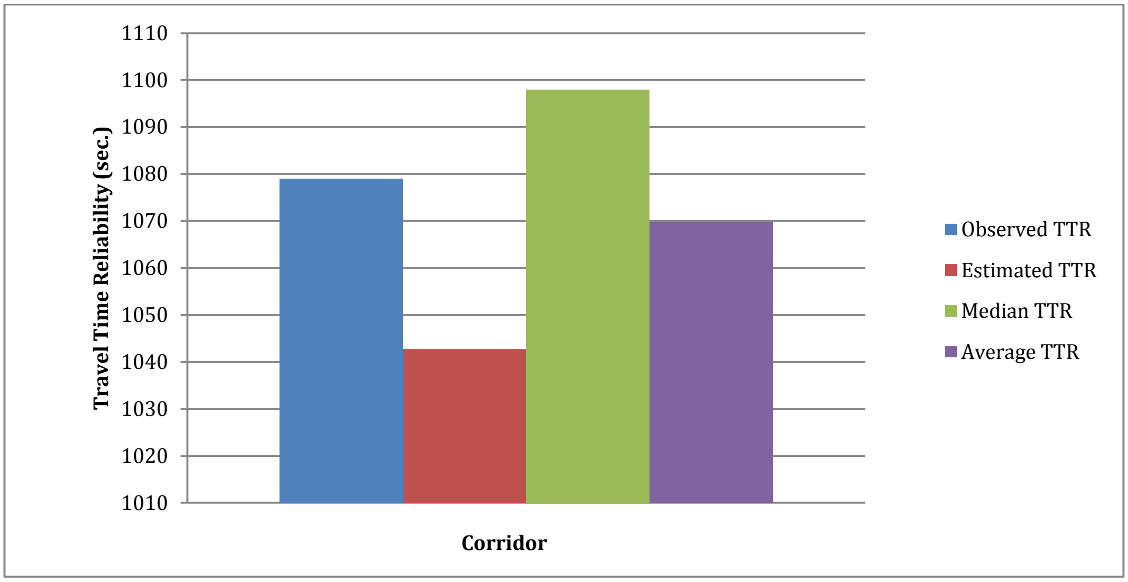


Figure 32: Travel Times Reliability Comparison for the Corridor between Observed and Estimated Data

Figure 31 shows that reliable travel times from equation [15] are in the range differential from 0.17 second to 15.93 seconds compared to the observed reliable travel times on the roadway. In addition, Figure 32 shows the observed reliable travel time for the entire corridor is 1079 seconds, whereas the average reliable travel time is 1067.33 seconds and the reliable travel time estimated by the model (validation) is 1042.72 seconds. This result demonstrates a difference of 36.28 seconds between the estimated travel time and observed data; and 11.67 seconds between the average reliable travel time and the observed data. These differences are in acceptable agreement for data validation; therefore, the model can be considered validated.

5.6 Generality of the Model

The field data used to construct models generally comes from a small number of sites covering a fraction of the area of interest. Therefore, assessing the generality of the model is important for data covering large geographical areas. A fundamental property of a model is its generality or range of applicability. Different levels of generality in the way a model is operating can affect efficiency. Specific reasoning methods are very efficient, but typically analysts apply them only in few situations. General models provide flexibility for a variety of tasks.

The model generality will be verified by selecting two road segments from two major corridors (University Parkway and Fruitville Road) in Sarasota County, FL (See Figure 33). These corridors are both six lane divided roadways with divers traffic and geometric characteristics, as well as adjacent land use and development features. Data from Sarasota County 2008 Annual Corridor Travel Time and Delay Study are used to generalize the model. Sarasota County Traffic Engineering and Operations Divisions deployed an automated data collection method (Time-Space/Platoon Progression Diagram Generator (TS-PP/Draft) with Average Car Technique to collect travel times as the vehicle traverses the study route for six (6) runs in each direction during morning (7:00 to 9:00) and afternoon (4:00 to 6:00) peak periods. The average travel times (the travel time reliability for Sarasota County is based on LOS, which is different than the reliability measure considered for this dissertation) for westbound direction during the morning peak periods will be considered for the model generality and robustness. The different segment attributes are illustrated in Table 56.

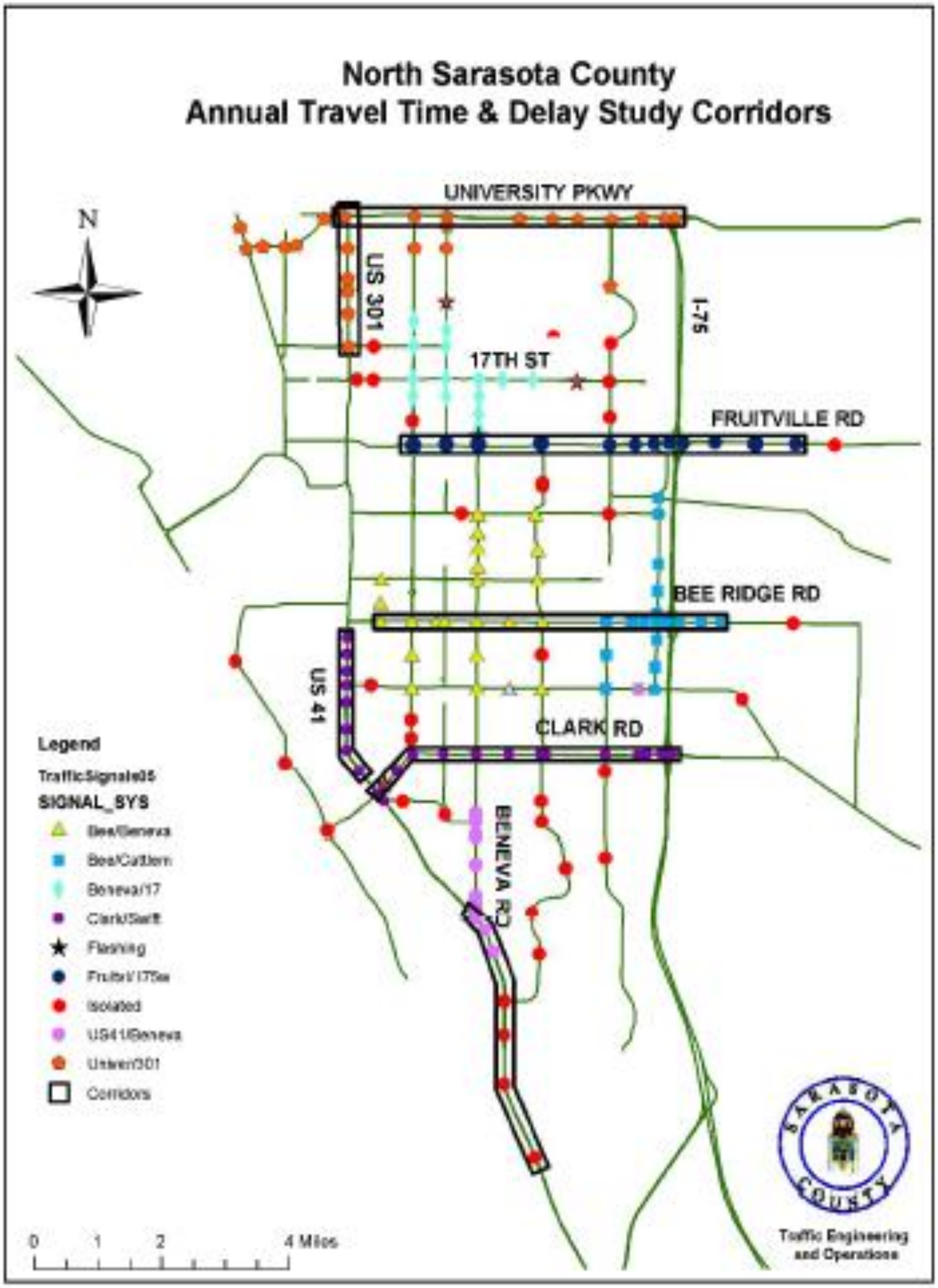


Figure 33: Selected Corridors from Sarasota County, FL
Source: Sarasota County, Traffic operations and Engineering

Table 56: Segment Attributes for Model Generality and Robustness

	Corridors	
	University Parkway	**Fruitville Rd**
X_1	50	45
X_2	130	140
X_3	45240	57512
X_4	0.5	0.5
X_5	4	4
X_7	1	1
X_9	25	20
X_{11}	600	300
X_{13}	0	1
X_{15}	300	70
Y	44.5	54.7

where Y (Average Travel Times); X_1 (Posted Speed); X_2 (Signal Timing Cycle Length); X_3 (AADT major road); X_4 (Arterial Segment Length); X_5 (Number of Intersection Legs); X_7 (Exclusive RT minor road); X_9 (Number of Lanes @ Intersection), X_{11} (left Turn Lane Major Road) X_{13} (Right Turn Lane Major Road); X_{15} (Left Turn Lane Minor Road).

For instance, consider the segment from the University Parkway corridor and its attributes.

Equation [15] becomes:

$36.198-2.105*50-0.262*130+0.001*45240+111.192*0.50-3.551*4+6.409*1$ $+1.166*25+0.055*300+0.056*0+0.025*300=43.96$ which is 0.34 (44.30-43.96) seconds higher than the reliable travel time on the roadway.

The same process is applied for the segment from Fruitville Road corridor and the results are showed on Table 57.

Table 57: Travel Time Reliability Comparison for Model Generality and Robustness

Corridors	Average TT (sec.)	Expected TT (sec.)	TT Difference (sec.)
University Parkway	44.30	43.96	0.34
Fruitville Road	54.7	50.62	4.08

Table 57 shows slight differences between reliable travel times from the linear regression model and travel times from the field tests. These differences can be attributed to travel time data collection methods, the areas socio demographic characteristics (e.g., drivers' age groups, drivers' aggressiveness, location and type of activities).These differences also verify the model generality and robustness.

5.7. Scenarios-Marginal Effects

In the scenario analysis, the attributes of the segments are modified to determine the impacts on travel times and travel time reliability for the entire corridor. Two influencing factors left turn lane on minor road (X_{15}) and posted speed (X_1) are considered for modification. In the first scenario, by prohibiting the left turn on all the segments and without changing the other attributes, all the segments become more reliable (decrease in travel time threshold). In the second scenario, by increasing the posted speed by 12.50 % (from 40 MPH to 45 MPH) on segments # 2001 and # 1002 from their original geometric design and keeping the other attributes unchanged, the travel time thresholds (reliability) on segments # 2001 and # 1002 decrease by 78.73% and 66.89% respectively. Additionally, travel time threshold (reliability) on the corridor decreases by 53.59 % and 49.58% respectively for the scenarios, which indicates that the first scenario could be a better method to improve travel time on the corridor.

Tables 58 and 59 illustrate the two scenarios where base TTR (column 4) is the predicted travel time reliability and % Change RTT (column 6) is the percentage increase/decrease in reliable travel times from the different segments in comparison to the predicted RTT. Column 2 (X_{15}) and column 3 (X_{15} Modified) are the number of left turn lane on minor road from the original roadway geometric design and number of left turn lane modified respectively. In addition, Table 60 illustrates the percentage increase/decrease in TTR for the corridor for the scenarios where Y (column 2) is the predicted TTR and Y' (column 3) is TTR after modifying X_{15} and X_1.

Table 58: Travel Time Reliability Comparison for the Segments by Modifying X_{15}

Segment #	**X_{15}**	**X_{15} Modified**	**Predicted TTR**	**Scenario 1**	**% Change RTT**
9008	600	0	141	65.07	53.25
8007	0	0	103	65.19	36.70
7006	580	0	136.6	53.4	60.90
6005	270	0	123	62.53	49.16
5004	620	0	67.1	19.77	70.53
4003	0	0	104	47.84	54
3002	120	0	73	17.80	75.61
2001	0	0	111.3	34.19	69.28
1002	0	0	75	35.35	52.86
2003	200	0	53	19.87	62.50
3004	0	0	102.1	60.92	40.33
4005	105	0	75	12.49	83.34
5006	420	0	156	100.66	35.47
6007	125	0	68.1	36.95	45.74
7008	650	0	186.1	92.60	50.24
8009	110	0	83	43.60	47.46

Table 59: Travel time Reliability Comparison for the Segments by Modifying X_1

Segment #	X_1	X_1 Modified	Predicted TTR	Scenario 2	% Change RTT
9008	50	50	141	79.96	43.33
8007	50	50	103	65.17	36.72
7006	50	50	136.6	67.84	101.35
6005	50	50	123	69.28	43.67
5004	50	50	67.1	35.27	47.43
4003	45	45	104	47.84	54
3002	45	45	73	20.8	71.50
2001	40	45	111.3	23.67	78.73
1002	40	45	75	24.83	66.89
2003	45	45	53	24.87	53.07
3004	45	45	102.1	60.92	40.33
4005	50	50	75	15.12	79.84
5006	50	50	156	104.75	32.85
6007	50	50	68.1	33.67	50.55
7008	50	50	186.1	115.26	38.06
8009	50	50	83	46.36	44.15

Table 60: Travel Time Reliability Comparison for the Corridor by Modifying X_1 & X_{15}

	Y	Y’	% Change RTT
Scenario 1	1657.4	769	53.59
Scenario 2	1657.4	835	49.58

5.8 Guidance on Roadway Design, Traffic Design, Traffic Operations, and Access Management

Two distinct approaches characterize and define improving travel time reliability on urban arterials. First, newly constructed facilities in newly acquired rights of way allow for additional capacity and network connections. Second, existing facilities in the urban area can be upgraded both in design and operational aspects to provide increased capacity, safety, congestion reduction walkability, or other goals. These two design approaches are necessary to meet different users of the urban highway network who have different requirements for travel time reliability. Conversely, in practice, many professionals working in the design field have been oriented toward only one of the approaches with little contact or interest of the other type of design.

In summary, to improve travel time on urban corridors:

- All the segments on existing facilities and their attributes should be considered separately and traffic operations on the entire corridor should be coordinated. In the case of an already coordinated corridor, increasing the green split and retiming the signals can decrease travel time. However, increasing the green split could have an important effect on average delay.
- For new facilities to be built in newly acquired rights of way, the segment length should be longer than 0.50 miles and the posted speed in the range of 45 MPH to 55 MPH. Building frontage roads that run parallel to the urban arterials can decrease the access density at the focal points between interchanges and these arterials where new shopping centers, industrial parks, and office complexes are increasingly located.

Chapter 6- Limitations and Contributions

6.1 Summary of Limitations

This dissertation has some limitations:

- First, some variables have signs that are contrary to expectations and the dissertation did not provide a full explanation of these “wrong signs”, which could be attributed to the following:
    1) Lurking variables: the variable in question is a proxy for other variables that are excluded from the analysis.
    2) Multicollinarity: When two or more explanatory variables are not independent, the sign of the coefficients of one of the variables may differ from the sign of that coefficient if the variable were the only explanatory variable. That is confounded variable.
- Second, travel time data was collected on one corridor. Even though over 3,500 data sets were collected and analyzed, travel time data on several corridors with divers attributes could help compare these factors variation on different corridors.
- Third, other potential significant factors were not considered such as lane width and median type. The former varies from 10 feet to 12 feet on most urban arterials. This minor difference in width can be significant on travel time reliability in industrial areas with high truck volumes. The later consisting of OWLTL or TWLTL (one- or two-way left- turn lanes), flush median, raised

median among others is correlated to access density, which in return is a significant factor to travel time reliability.

- Fourth, the model is a better tool for LRPT (Long Range Transportation Planning) purposes than daily traffic/ roadway design applications.

6.2 Summary of Contributions

Despite these limitations, the dissertation offered several contributions to the State-of-the-Art, which are listed below:

- A Linear Regression Model that identifies 10 factors that significantly influence travel time reliability on urban arterials for recurrent conditions. Arterial Segment Length is the most contributing factor whereas signal timing cycle length is the least contributing factor. Identifying these factors is a key contribution to HCM and AASHTO where studies are being conducted to include reliability factors into roadway design features. By explaining 67.4% of the observed data, this model outperforms current models and performs well or better than a range of state-of-the-art travel time reliability models described in the literature review.
- The correlation among the influencing factors, which is necessary for traffic operations, traffic design, and long range transportation planning. The correlation explains the contributing impacts of other factors on travel time reliability improvement on a corridor by modifying one factor. In other words, the resulting travel time reliability improvement is due not only to the modified factor but also to other factors that are correlated to it.

- The travel time reliability threshold based on buffer time (travel time reliability calculation method) was experimented on urban arterials. Unlike many other travel time reliability measures, the buffer time can be easily communicated to technical audiences (e.g., traffic engineers, transportation planners, MPO members) and non-technical audiences (e.g., daily travelers, business owners, truck drivers), in particular, policy makers should funding be needed to improve travel time reliability on a corridor.
- The linear regression model has demonstrated the importance of a new data collection method, the VD240 wireless vehicle detention system from Sensys Networks ATTS. Compared to other travel time data collection methods, the ATTS appears to be the one deployed that provides an accurate real-time estimate of the travel time distribution and traffic counts. Additionally, the mean travel time as well as its standard deviation or 80th percentile is estimated. The model was proved to be neither "black-box" or location-specific by demonstrating its robustness and generality in comparison to other travel time data collected in different urban arterials.

6.3 Implications and Recommendations for Future Research

- This dissertation has established baselines for researches to identify the other influencing factors which represent 32.6% of the observed data. These factors could be attributed to driving behavior, driver group age, traffic congestion, inadequate lane capacity, month of the year, location of activities, special events or non-recurrent events (e.g., crashes, rain, and construction/maintenance activity).

- Further research need to be conducted on the correlation between the number of exclusive left turn lane from cross streets and travel time reliability on the major arterials. This dissertation has demonstrated that adding an exclusive left turn lane on a cross street to improve traffic operations features can hamper travel time reliability on the main street. This research should include left turn lane volume on cross street, AADT on cross street, and exclusive left turn signal timing cycle length.
- The equation from the model can be considered as theoretical and for practical applications, the influencing factors with low coefficients can be removed.
- Urban travel time databases from Sensys Networks ATTS need to include non-recurrent events (e.g., crashes, rain, roadway construction/maintenance activity), and special events information. This information could help identify other contributing factors to travel time reliability on urban arterials.
- Peak hour traffic volumes and vehicle traffic composition (% of heavy trucks) should be considered as potential influencing factors instead of AADs and VPHPL if these data are available.
- Quality of signal timing (good coordination versus bad coordination) and functionality of the detectors should be considered as potential influencing factors instead of signal timing cycle length if these data are available.
- Left/Right turn lane major (minor) road can be considered as dummy variable instead of continuous variable and land use to be considered as a potential influencing factor.

References

1. Aiken, L. S., and West, S. G. (1991). *Multiple regression: Testing and interpreting interactions.* Sage-Publications, Newbury Park, London.

2. Al-Deek, H. and Emam, E. (2006). *New methodology for estimating reliability in transportation networks with degraded link capacities*. Journal of Intelligent Transportation Systems, 10 (3), 117-129.

3. Boyles, S., Voruganti, A., and Waller, S. (2010). *Quantifying Travel time Variability in Transportation networks*. Center for Transportation Research, University of Texas, Austin, Texas.

4. Chen, C., Skabardonis, A., and Varaiya, P., (2003). *Travel Time Reliability as a Measure of Service*. Transportation Research Record 1855, Transportation Research Board, Washington, DC, pp. 74-79.

5. Clark, S. D., and .Watling, D.P. (2005). *Modeling Travel Time Reliability under Stochastic Demand*. Transportation Research. Pat B: Methodological 39(2), pp. 119-140.

6. Cambridge Systematics, Inc., High Street Consulting Group, TransTech Management, Inc., Spy Pond Partners, Ross & Associates (2009). *Performance Measure Framework for Highway Capacity Decision Making*, NCHRP Report 618, Transportation Research Board of National Academies, Washington, DC.

7. Cambridge Systematics, Inc.; Dowling Associates, Inc.; System Metrics Group, Inc.; Texas Transportation Institute (2008). *Cost-Effective Performance Measures for Travel Time Delay, Variation, and Reliability*, NCHRP Report 618, Transportation Research Board, Washington, DC.

8. Dawson, J. F., & Richter, A. W. (2006). *Probing three-way interactions in moderated multiple regression: Development and application of a slope difference test*. Journal of Applied Psychology, 91*, pp.* 917-926.

9. Dowling, R. et al., (2009). *Reliability Breakpoints on Freeways*. Paper # 09-0813, Transportation Research Board, Washington, DC.

10. Elefteriandou, L., and Xu, H. (2007). *Travel Time Reliability Models for Freeways and Arterials.* Transportation Research Center, University of Florida, Gainesville, FL. http://www.dot.state.fl.u PL/FDOT_BD545_70_rptb.pdf.

11. Florida Department of Transportation (DFOT) (2000). *The Florida reliability method: In Florida's mobility performance measures program*. Available at: http://www.dot.state.fl.us/planning/statistics/mobilitymeasures/reliability.pdf, accessed on June 2008.

12. Frey, W. H., (2003). *Boomers and Seniors in the Suburbs: aging Patterns in census 2000*. Brookings Census 2000 Series, Washington D.C.: Brookings Institute-Center on Urban and Metropolitan Policy.

13. Garber, J. G., and Hoel, L. (2009). *Traffic and Highway Engineering, 4th edition* 2nd Edition, Cengage Learning Press, Toronto, Canada.

14. Hollander, Y. (2006). *Direct Versus Indirect Models for the Effects of Unreliability.* Transportation Research A, Vol. 40, Issue 9, pp. 699-711.

15. *Highway Capacity Manual, 4th Edition* (2000). Transportation Research Board, National Research Council, Washington DC.

16. Insurance Institute for Highway Safety (2000). *Traffic Engineering Approaches to Reduce Crashes on Urban Arterial Roads*. Available at: http://www.highwaysafetyihs_traffic_approaches.pdf, accessed on October 2008.

17. Kavaler, R., Kwong, K., and Raman, A. (2009). *Arterials Performance Measurement with Wireless Magnetic Sensors*. Journal of the American Society of Civil Engineers, Volume 1: Highway Transportation, pp. 377-385.

18. Liping, F., Hellinga, B., and Yongliang, Z. (2001). *An Adaptive Model for Real-Time Estimation of Overflow Queues on Congested Arterials*. Intelligent Transportation Systems, pp. 219-226.

19. Liu, H., Vant Lint, H. and Zuylen, H. (2006). *Neutral Network Based Traffic Flow for Urban Arterial Travel Time Prediction*. Faculty of Civil Engineering and Geosciences, Delft University of Technology.

20. Lomax, T., Schrank, D., and Turner, S. (2003). *Selecting Travel Time Reliability Measures.* Available at: http://tti.tamu.edu/documents/TTI-2003-3.pdf, accessed on February 2010.

21. Lomax, J., Schrank, D., and Eisele, W. (2005). *The Keys to Estimating Mobility in Urban Areas: Applying Definitions and Measures That Everyone Understands*. Texas Transportation Institute, The Texas A&M University System. Available at: (http://mobility.tamu.edu).

22. Lowrey, A. (2011). *Your Commute is Killing You: Long Commutes Cause Obesity, Neck Pain, Loneliness, Divorce, Stress and Insomnia*. Slate. Available at: http://www.slate.com/id/2295603.

23. McShane, W., and Crowley, K. (1976*). Regularity of Some Detector-Observed Arterial Traffic Volume Characteristics*. Transportation Research Record 596, Transportation Research Board, Washington DC, pp. 33-37.

24. Miou, S. P. (1994). *The Relationship between Truck Accidents and Geometric Design on Road Sections: Poisson versus Negative Binomial Regressions*. Accident Analysis and Prevention 26, 471-482.

25. Myers, R. H. (1990). *Classical and Modern Regression with Applications*, 2nd Edition, Duxbury Press, Belmont, CA.

26. Nam, D., Park, D., and Khamkongkhun, A. (2005). *Estimation of Value of Travel Time Reliability*. Journal of Advanced Transportation, Vol. 39, Issue 1, pp. 39-61.

27. Pedersen, N. and Sandahl, D. (1982). *Highway Traffic Data for Urbanized Area Project Planning and Design*. NCHRP Report 255. Transportation Research Board. Washington, DC.

28. O'Shea, J., Rioux, T., and Machemehl, R. (2001). Project 0-1846: *Development of Design Guidelines for the Provision of Median Access on Principal Arterials*. Center for Transportation Research, University of Texas, Austin.

29. Pisarski, A. (2006). *Commuting in America III*. Available at: http://www.trb.org/Main/Public/Blurbs/156993.aspx, accessed on April 2007.

30. Pu, W. (2010). *Analytic Relationships between Travel Time Reliability Measures*. Transportation Research Record 2254, Transportation Research Board, Washington, DC, pp 122-130.

31. Texas Transportation Institute. *2007 Annual Urban Mobility Report*. Available at: http://mobility.tamu.edu/ums/report, accessed on October 2009.

32. Texas Transportation Institute. *2011 Annual Urban Mobility Report*. Available at: http://mobility.tamu.edu/ums/report, accessed on February 2012.

33. Tobin, J. (1958). Estimation of Relationships for Limited Dependent Variables. Econometrica 26, pp. 24-36.

34. Train, K. (1978). *A Validation Test of a Disaggregate Mode Choice Model* Transportation Research, Vol. 12, pp. 167-174).

35. Train, K. and Winston, C. (2007). *Vehicle Choice Behavior and the Declining Market Share of US Automakers*. International Economic Review, Vol. 48, No. 4, pp. 1469-1496.

36. U.S. Census Bureau, U.S. Population Projection by Age, Sex. Available at: http://www.census.gov/, accessed on February 2010.

37. U.S. Department of Transportation, Federal Highway Administration (FHWA) (2006). *Travel Time Reliability: Making it There on Time, All the Time*. Available at http://ops.fhwa.dot.gov/publications/tt_reliability/TTR_Report.htm Accessed on January 2007.

38. Van Lint, J.W.C., (2004). *Reliable Travel Time Prediction for Freeways.* Dissertation submitted in fulfillment of the Ph.D. in Civil Engineering, Delft University of Technology, Netherlands.

39. Washburn, S.S., McLeod, D.S., and Courage, K. G. (2002). *Adaptation of the HCM2000 Planning Level Analysis of Two-Lane and Multilane Highways in Florida*. Transportation Research Record 1902, Transportation Research Board, Washington, DC, pp. 62-68.

40. Washington, S. P., M., Karlaftis, G. M., and Mannering F. L. (2003). *Statistical and Econometric Methods for Transportation Data Analysis*. Chapman and Hall Press, Boca Raton, FL.

41. Yang, J.-S., (2006). *A Nonlinear State Space Approach to Arterial Travel Time Prediction*. Department of Electrical & Computer Engineering, University of Minnesota, Duluth. http://conservancy.umn.edu/bitstream/1020/1/200605.pdf.

42. Wasson, J.S, Sturdevant, J. and Bullock, D. (2008). *Real-Time Travel Times Estimates Using Media Access Control Address Matching*. ITE Journal, Volume: 78, Issue: 6, pp.20-23.

43. Williams, W. and Welch, H. (1997). *Sensitivity of Transport Investment Benefits to the Evaluation of Small Travel-Time Savings*. Journal of Transport Economics and Policy, Vol. 31, No. 3, Sept., pp. 231-254.

Appendices

Appendix A- Travel Times for the Segments for Peak Periods - Driving Westward

Time/AM	**9008**	**8007**	**7006**	**6005**	**5004**	**4003**	**3002**	**2001**
605	81	65	44	85	30	42	25	20
610	57	65	34	91	55	44	21	17
615	56	62	45	62	45	63	33	22
620	62	65	71	68	46	50	27	30
625	74	66	66	73	38	68	19	49
630	82	66	47	75	40	57	47	21
635	84	62	42	52	49	43	40	37
640	102	71	66	78	61	65	38	42
645	90	68	79	83	48	66	36	54
650	85	75	94	86	61	70	44	56
655	89	67	128	107	65	70	50	43
700	111	60	114	112	63	78	61	59
705	124	72	105	107	44	64	47	100
710	111	70	121	67	97	69	54	39
715	129	66	137	60	67	84	51	28
720	111	79	139	66	64	90	56	90
725	143	80	169	66	114	85	59	78
730	140	70	165	70	66	83	62	68
735	86	65	139	134	66	65	43	103
750	100	65	57	80	66	92	56	62
745	66	104	82	125	64	89	61	146
750	139	103	109	94	55	85	56	116
755	45	74	145	99	46	57	53	52
800	145	89	109	112	52	87	62	69
805	161	67	76	86	55	51	65	48
810	113	69	112	129	36	40	61	37
815	93	71	104	54	61	73	59	67
820	110	98	95	109	52	80	55	32
825	98	74	86	103	50	72	44	61
830	106	68	92	122	24	57	82	42
835	80	68	78	100	58	44	54	42
840	89	78	88	99	41	94	61	45
845	55	74	95	89	39	43	29	45
850	118	67	98	80	62	82	71	66
855	101	65	113	136	26	51	54	52
900	88	67	111	92	51	79	62	56

Appendix A (Continued)

Time/PM	9008	8007	7006	6005	5004	4003	3002	2001
400	110	70	89	107	50	82	56	59
405	125	96	111	62	57	95	65	55
410	57	83	102	115	30	152	67	47
415	111	90	87	61	50	42	63	49
420	121	103	100	116	46	46	58	29
425	114	70	103	108	57	97	61	53
430	96	71	77	96	65	46	68	47
435	118	93	90	71	44	66	56	82
440	120	87	96	115	63	98	73	39
445	106	76	62	120	68	84	54	55
450	101	66	101	71	58	82	67	25
455	111	103	86	103	26	101	16	42
500	107	87	103	102	98	84	64	41
505	106	96	88	100	51	46	54	54
510	97	107	106	118	64	41	67	43
515	71	67	76	66	59	114	65	61
520	126	98	69	105	34	62	66	39
525	106	83	100	122	62	88	61	45
530	92	69	74	93	59	63	65	51
535	130	69	112	119	60	85	64	69
540	140	67	88	94	59	114	67	43
545	111	99	122	97	66	117	56	51
550	121	98	105	92	33	93	65	47
555	114	104	80	113	60	58	44	55
600	100	95	95	97	58	104	53	51
605	117	105	97	99	62	42	60	53
610	124	72	89	82	100	53	14	54
615	123	104	42	95	27	96	61	52
620	98	67	62	97	48	45	40	37
625	95	66	110	119	27	42	59	41
630	71	65	89	100	53	62	70	49
635	114	64	97	96	47	42	55	71
640	118	71	87	112	56	69	56	60
645	135	70	62	61	57	104	66	51
650	114	71	98	94	51	62	59	61
655	175	78	100	92	53	77	58	34
700	102	81	76	121	60	98	46	163

Appendix A (Continued)

Time/AM	9008	8007	7006	6005	5004	4003	3002	2001
605	71	65	42	62	32	41	38	42
610	66	56	60	79	36	50	23	19
615	88	60	49	62	46	47	23	43
620	85	67	48	75	41	41	41	26
625	80	62	40	63	33	58	56	18
630	82	63	62	61	46	51	29	70
635	65	59	85	66	53	65	15	30
640	106	62	83	66	24	45	35	32
645	96	68	25	104	42	74	37	49
650	91	66	85	81	50	64	43	41
655	99	81	115	83	49	72	44	52
700	108	72	117	112	45	39	36	45
705	111	66	112	97	46	71	35	67
710	135	64	27	57	53	75	48	25
715	88	78	111	64	63	77	57	48
720	111	76	93	127	58	77	58	63
725	115	91	137	63	58	80	59	123
730	104	70	207	70	64	79	52	111
735	125	111	121	112	62	71	59	108
750	130	110	99	81	65	63	46	114
745	89	67	116	105	58	76	100	119
750	171	75	103	107	59	75	62	120
755	112	69	151	120	42	64	74	72
800	107	65	95	97	65	89	80	49
805	89	66	115	92	56	45	58	62
810	88	68	104	111	52	44	62	49
815	138	66	113	62	45	42	52	60
820	143	86	118	108	51	52	54	87
825	122	94	107	111	62	93	70	52
830	119	84	111	72	52	82	52	60
835	37	74	59	124	66	86	49	59
840	96	63	89	94	26	38	71	67
845	133	77	98	98	34	43	62	42
850	147	78	105	63	64	45	58	43
855	118	75	108	100	50	110	55	55
900	124	65	86	107	59	73	59	30

Appendix A (Continued)

Time/AM	**9008**	**8007**	**7006**	**6005**	**5004**	**4003**	**3002**	**2001**
605	71	65	42	62	32	41	38	42
610	66	56	60	79	36	50	23	19
615	88	60	49	62	46	47	23	43
620	85	67	48	75	41	41	41	26
625	80	62	40	63	33	58	56	18
630	82	63	62	61	46	51	29	70
635	65	59	85	66	53	65	15	30
640	106	62	83	66	24	45	35	32
645	96	68	25	104	42	74	37	49
650	91	66	85	81	50	64	43	41
655	99	81	115	83	49	72	44	52
700	108	72	117	112	45	39	36	45
705	111	66	112	97	46	71	35	67
710	135	64	27	57	53	75	48	25
715	88	78	111	64	63	77	57	48
720	111	76	93	127	58	77	58	63
725	115	91	137	63	58	80	59	123
730	104	70	207	70	64	79	52	111
735	125	111	121	112	62	71	59	108
750	130	110	99	81	65	63	46	114
745	89	67	116	105	58	76	100	119
750	171	75	103	107	59	75	62	120
755	112	69	151	120	42	64	74	72
800	107	65	95	97	65	89	80	49
805	89	66	115	92	56	45	58	62
810	88	68	104	111	52	44	62	49
815	138	66	113	62	45	42	52	60
820	143	86	118	108	51	52	54	87
825	122	94	107	111	62	93	70	52
830	119	84	111	72	52	82	52	60
835	37	74	59	124	66	86	49	59
840	96	63	89	94	26	38	71	67
845	133	77	98	98	34	43	62	42
850	147	78	105	63	64	45	58	43
855	118	75	108	100	50	110	55	55
900	124	65	86	107	59	73	59	30

Appendix A (Continued)

Time/PM	**9008**	**8007**	**7006**	**6005**	**5004**	**4003**	**3002**	**2001**
400	110	85	80	77	46	48	68	57
405	122	64	31	115	27	89	65	53
410	99	74	97	105	56	45	65	55
415	107	79	70	91	63	82	61	42
420	133	96	101	113	48	75	54	38
425	98	70	109	116	62	63	73	85
430	93	79	94	102	46	44	66	53
435	85	78	68	99	64	83	65	47
440	114	86	65	104	50	54	59	59
445	117	103	85	109	41	44	61	41
450	113	69	107	103	53	79	62	61
455	119	70	104	103	63	43	67	49
500	115	94	114	111	51	79	61	58
505	109	70	107	82	64	91	63	72
510	160	85	86	112	58	39	62	57
515	100	81	93	101	63	81	58	70
520	109	103	98	89	68	47	59	62
525	111	88	109	112	53	42	74	65
530	119	76	86	114	31	63	67	37
535	95	71	113	114	52	42	70	32
540	96	78	88	85	58	96	66	56
545	119	92	108	106	27	78	60	50
550	124	86	106	68	59	83	56	57
555	117	94	102	82	66	91	56	54
600	101	90	105	118	50	97	60	65
605	130	85	74	61	61	76	52	82
610	83	74	119	97	41	52	47	43
615	90	68	49	115	56	89	68	47
620	108	74	93	75	25	80	63	53
625	95	82	90	103	59	68	65	46
630	108	82	104	115	55	49	70	54
635	127	100	90	115	52	50	53	62
640	125	68	76	123	27	78	38	61
645	122	70	98	64	41	73	49	72
650	133	101	52	81	35	137	54	66
655	90	74	73	98	53	81	41	64
700	105	84	79	103	64	88	65	48

Appendix B- Travel Times for the Segments for Peak Periods - Driving Eastward

Time/PM	**1002**	**2003**	**3004**	**4005**	**5006**	**6007**	**7008**	**8009**
400	68	37	71	30	173	39	128	94
405	62	14	78	39	137	44	160	68
410	74	38	99	40	116	42	150	68
415	76	37	90	28	59	43	130	78
420	69	28	76	31	130	44	141	53
425	73	16	85	29	110	39	141	59
430	71	17	74	34	133	69	183	58
435	58	43	99	33	136	35	162	60
440	72	36	77	38	122	55	151	57
445	70	38	106	48	131	52	165	62
450	74	48	101	55	97	60	175	65
455	68	23	94	33	121	38	170	51
500	72	54	92	29	146	41	84	59
505	79	48	85	29	128	57	155	65
510	74	32	75	31	143	55	213	70
515	74	53	89	48	104	41	185	71
520	71	24	100	43	136	65	139	50
525	67	20	76	40	84	43	156	68
530	66	26	101	28	124	39	155	62
535	80	14	61	42	117	42	149	77
540	75	63	76	42	148	67	135	65
545	60	44	83	30	136	46	144	60
550	73	41	95	50	172	40	150	50
555	66	35	80	41	145	48	157	64
600	65	38	70	108	121	64	160	54
605	69	17	98	46	88	50	201	59
610	74	46	89	28	132	44	205	69
615	71	14	90	31	139	55	156	76
620	59	67	58	48	139	42	118	53
625	64	45	81	45	135	41	149	67
630	74	19	80	29	107	58	142	62
635	49	30	105	41	124	62	125	63
640	64	16	88	93	107	59	166	80
645	65	53	97	27	127	79	143	68
650	58	33	84	66	80	37	139	53
655	52	15	102	30	104	52	138	83
700	61	23	88	30	92	36	140	72

Appendix B (Continued)

Time/PM	1002	2003	3004	4005	5006	6007	7008	8009
400	66	16	86	28	101	53	185	85
405	70	15	65	82	115	42	173	58
410	61	41	76	30	129	80	139	62
415	73	33	90	28	176	45	154	67
420	62	15	80	27	141	50	145	60
425	74	17	81	26	113	55	132	64
430	72	35	94	48	136	55	159	39
435	72	27	88	28	186	39	146	73
440	77	40	83	27	136	38	182	73
445	79	15	79	32	123	44	119	64
450	72	47	63	25	88	60	173	55
455	55	19	71	40	126	42	160	81
500	78	36	78	32	129	59	187	97
505	64	38	99	29	125	51	118	85
510	64	37	107	36	127	45	157	68
515	57	16	77	32	120	38	216	73
520	70	16	91	29	128	39	197	69
525	74	41	97	35	154	62	94	76
530	67	44	97	39	132	35	169	76
535	68	30	81	35	112	38	110	53
540	66	46	93	32	156	48	175	60
545	68	13	105	31	156	38	154	69
550	72	25	55	27	163	39	189	70
555	70	14	101	35	131	49	179	66
600	62	16	85	38	129	56	155	60
605	75	18	78	33	113	41	213	70
610	71	39	84	40	155	44	143	73
615	59	30	81	30	124	44	125	78
620	46	31	83	33	143	40	170	54
625	73	18	82	29	114	58	186	63
630	64	18	92	43	139	39	171	54
635	58	16	65	57	114	41	147	52
640	56	15	88	79	113	49	131	120
645	67	21	74	32	88	46	190	57
650	67	15	96	74	113	55	151	51
655	58	16	90	75	171	40	166	66
700	64	57	79	42	113	39	145	51

Appendix B (Continued)

Time/AM	**1002**	**2003**	**3004**	**4005**	**5006**	**6007**	**7008**	**8009**
605	20	18	40	22	73	32	89	38
610	26	33	46	22	75	34	0	37
615	37	13	4	22	82	36	60	41
620	33	16	40	22	81	38	54	33
625	27	14	86	22	86	39	65	36
630	29	18	60	22	84	37	102	31
635	42	15	40	22	75	38	12	35
640	41	24	73	22	76	32	93	54
645	103	13	80	22	86	39	93	54
650	48	35	86	17	77	37	141	56
655	47	38	74	21	76	38	142	54
700	24	17	60	21	78	36	129	59
705	50	23	75	21	124	37	85	41
710	60	39	91	21	110	50	228	29
715	52	13	86	27	147	42	92	83
720	49	117	46	27	127	58	141	57
725	48	13	85	27	142	39	152	54
730	61	39	107	27	140	36	80	57
735	49	49	76	30	156	42	152	55
750	58	15	130	30	183	84	119	59
745	64	16	86	30	127	64	124	33
750	60	14	70	36	180	45	123	78
755	56	50	114	25	138	80	81	78
800	67	22	79	19	126	59	15	50
805	64	21	58	19	149	38	15	55
810	52	24	92	19	134	52	113	40
815	68	14	83	16	80	54	159	49
820	63	15	63	26	134	42	128	46
825	58	15	77	22	93	53	131	54
830	50	69	68	28	119	49	114	76
835	69	56	56	21	122	58	116	53
840	57	16	68	21	102	41	142	68
845	70	18	92	36	131	54	119	56
850	56	20	59	18	92	55	132	60
855	57	26	64	36	113	55	119	59
900	57	60	54	42	127	37	109	58

Appendix B (Continued)

Time/PM	1002	2003	3004	4005	5006	6007	7008	8009
400	107	16	57	80	127	64	73	47
405	60	15	54	33	152	59	149	57
410	73	22	90	31	119	39	147	61
415	72	20	86	28	109	37	130	54
420	69	51	62	46	124	80	137	55
425	75	33	86	34	114	61	151	90
430	59	42	74	34	118	56	141	69
435	64	38	102	27	111	38	136	105
440	68	13	55	31	105	40	133	61
445	64	37	84	35	129	57	154	61
450	77	15	88	35	109	61	159	67
455	68	13	84	38	116	39	153	61
500	67	19	97	34	123	38	152	61
505	57	27	76	33	135	55	135	44
510	63	14	90	33	137	42	157	65
515	70	36	73	37	108	41	154	68
520	63	16	101	28	133	59	149	53
525	58	41	100	31	125	53	145	64
530	63	17	95	49	128	39	137	64
535	66	17	84	39	126	39	177	56
540	68	51	81	28	96	39	137	56
545	62	42	91	30	125	45	145	59
550	68	38	71	35	174	40	123	63
555	58	49	61	26	154	37	175	65
600	71	40	79	37	125	59	160	51
605	62	14	68	44	113	41	182	72
610	65	16	132	28	137	40	135	62
615	60	48	99	34	147	49	123	112
620	72	22	70	43	147	48	139	61
625	62	24	100	44	57	60	131	59
630	62	20	88	27	126	47	164	77
635	66	17	94	75	95	98	142	134
640	71	28	91	80	69	40	158	61
645	53	38	94	73	141	95	146	47
650	49	50	96	74	107	62	154	63
655	58	20	86	68	131	40	139	53
700	52	16	96	57	114	40	130	73

Appendix C- List of Acronyms

AADT	Annual Average Daily Traffic
AASTHO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
ARIMA	Autoregressive Integrated Moving Average
ATT	Average Travel Time
ATTS	Arterial Travel Time Systems
BI	Buffer Index
BT	Buffer Time
CDF	Cumulative Distribution Function
CTMA	Chicago Traffic Management Authority
ETC	Electronic Toll Collection
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GIS	Geographic Intelligence Systems
GPS	Global Positioning Systems
HCM	Highway Capacity Manual
IDOT	Illinois Department of Transportation
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation Systems
LOS	Level of Service
LPR	License Plate Recognition
MPO	Metropolitan Planning Organization

Appendix C (Continued)

NCHRP	National Cooperative Highway Research Program
OCR	Optical Character Recognition
OLS	Ordinary Least Squares
OWLTL	One-Way Left-Turn Lane
PMCC	Pearson Moment Correlation Coefficient
RFID	Radio-Frequency Identification
SEM	Simultaneous Equation Model
SHRP	Strategy Highway Research Program
TMC	Traffic Management Center
TRB	Transportation Research Board
TS/PP-Draft	Time-Space/Platoon-Progression Diagram Generator
TT	Travel Time
TTR	Travel Time Reliability
TTRT	Travel Time Reliability Threshold
TWLTL	Two-Way Left-Turn Lane
VPHPL	Vehicle per Hour per Lane
VMT	Vehicle Mile Travelled
USDOT	U.S. Department of Transportation

Appendix D- Third Party Permissions

Good Evening Dr Pu,

Please let me know if it is permissible to use in my dissertation the table entitled "Travel Time Reliability Measures Recommended by Different Sources" from your 2010 technical paper "Analytic Relationship between Travel Times Reliability Measures".

Best regards,

Prony Bonnaire Fils, Ph.D. Candidate

Wenjing Pu wpu@mwcog.org
Apr 24 (2 days ago)
to me

Hi Prony,

Please feel free to use the table with clear citation from this paper. You may want to update the table since it is a bit old now. -Wenjing

About the Author

Prony received his Bachelor of Science in Civil Engineering from G.O.C University (Haiti) in 1994 and his Master of Science in Transportation Management from Universite Libre de Bruxelles (Free University of Brussels, Belgium) in 2000. He has over 15 years of professional experience in transportation planning and engineering, working for private, local/state agencies in Haiti and United States. Mr. Prony is very passionate about doing research and working as an international consultant in the third world where the transportation expertise available is defective. He is convinced that will be the most effective way, as a transportation professional, to save lives, preserve the environment, improve quality of life and contribute to social equality.