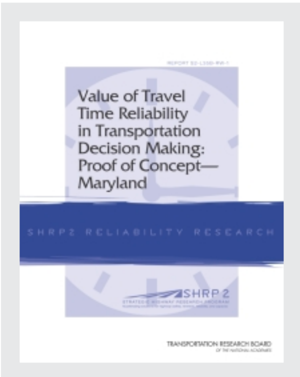


# Value of Travel Time Reliability in Transportation Decision Making: Proof of Concept—Maryland

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**AUTHORS**

Sadabadi, Kaveh Farokhi; Erdogan, Sevgi; Jacobs, Thomas H.;Ducca, Fredrick W.; and Lei Zhang

The Second
STRATEGIC HIGHWAY RESEARCH PROGRAM

SHRP 2 REPORT S2-L35B-RW-1

# Value of Travel Time Reliability in Transportation Decision Making: Proof of Concept—Maryland

**Kaveh Farokhi Sadabadi and Thomas H. Jacobs**
Center for Advanced Transportation Technology
University of Maryland

**Sevgi Erdogan and Fredrick W. Ducca**
National Center for Smart Growth Research & Education
University of Maryland

**Lei Zhang**
National Center for Strategic Transportation Policies, Investments and Decisions
University of Maryland

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The need for SHRP 2 was identified in *TRB Special Report 260: Strategic Highway Research: Saving Lives, Reducing Congestion, Improving Quality of Life,* published in 2001 and based on a study sponsored by Congress through the Transportation Equity Act for the 21st Century (TEA-21). SHRP 2, modeled after the first Strategic Highway Research Program, is a focused, time-constrained, management-driven program designed to complement existing highway research programs. SHRP 2 focuses on applied research in four areas: Safety, to prevent or reduce the severity of highway crashes by understanding driver behavior; Renewal, to address the aging infrastructure through rapid design and construction methods that cause minimal disruptions and produce lasting facilities; Reliability, to reduce congestion through incident reduction, management, response, and mitigation; and Capacity, to integrate mobility, economic, environmental, and community needs in the planning and designing of new transportation capacity.

SHRP 2 was authorized in August 2005 as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). The program is managed by the Transportation Research Board (TRB) on behalf of the National Research Council (NRC). SHRP 2 is conducted under a memorandum of understanding among the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and the National Academy of Sciences, parent organization of TRB and NRC. The program provides for competitive, merit-based selection of research contractors; independent research project oversight; and dissemination of research results.

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The project that is the subject of this report was a part of the second Strategic Highway Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical committee and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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Thomas H. Jacobs and Fredrick W. Ducca were co-principal investigators for this study. The primary authors of this report were Kaveh Farokhi Sadabadi and Sevgi Erdogan of, respectively, the University of Maryland's Center for Advanced Transportation Technology and National Center for Smart Growth Research & Education. Kaveh Farokhi Sadabadi led the development and application of the travel-time data-driven methodology for estimating value of reliability and wrote Part 2: Description of the Method. Other authors include the co-principal investigators and Lei Zhang of the University of Maryland's National Center for Strategic Transportation Policies, Investments and Decisions. Research support was provided by Richard A. Margiotta of Cambridge Systematics, Inc., and Julie Dunbar of Dunbar Transportation Consulting. The University of Maryland research team also acknowledges the technical contributions of Cinzia Cirillo at the University of Maryland, as well as Sabya Mishra at the University of Memphis.

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# FOREWORD

Ralph Hessian, P.Eng., FITE, *SHRP 2 Special Consultant, Capacity and Reliability*

Transportation agencies have traditionally used average travel times and travel time savings to measure system performance and benefits of improvement investments. The reliability of travel times from day to day has recently emerged as an important component of system performance for agencies and, of equal importance, for users who may rely on the roadway system for on-time arrival at their destinations. Unreliable travel can have significant negative consequences for individuals and businesses and thus requires that the value of reliability be considered in the selection of performance improvement projects. There is a need to understand the benefits of providing reliable travel time, establishing appropriate monetary values, and incorporating the additional dimension of travel time reliability into the economic analysis methods that support alternative project investment evaluations and programming decisions that will lead to better operational performance. This report will be of interest to transportation agencies and professionals involved in the analysis and selection of highway improvement projects for operational and capital programming.

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Traffic congestion continues to grow on the nation's highways, increasing the concerns of transportation agencies, the business community, and the general public. Congestion includes recurring and nonrecurring components. *Recurring congestion* reflects routine day-to-day delays during specific time periods when traffic demand exceeds available roadway capacity. Road users come to expect these daily traffic patterns and adjust their travel plans accordingly to achieve timely arrivals. *Nonrecurring congestion* results from random incidents such as crashes, weather, and work zones, which cause unexpected extra delays. Road users are frustrated by these unexpected delays, which can make for late arrival times at their destination. The SHRP 2 Reliability research objective focuses on reducing nonrecurring congestion through incident reduction, management, response, and mitigation. Achieving this objective will improve travel time reliability for both people and freight.

Earlier in SHRP 2 research, Reliability Project L11: Evaluating Alternative Operations Strategies to Improve Travel Time Reliability presented a novel approach to establishing an economic value for travel time reliability. The approach is based on the real options theory from the financial sector, in which an individual purchases an insurance premium to protect against an undesirable outcome. The travel analogy is when a traveler knows the normal travel time to a destination but chooses an earlier departure time to reduce the risk of a late arrival. This extra travel time has a monetary value and represents the insurance premium that a traveler is willing to pay. The method is data driven, using actual local historical travel times as the basis for establishing a value of reliability, whereas previous methods have used behavioral modeling techniques.

The Maryland State Highway Administration currently has a project development and programming process to address short-term congestion relief that includes the value of travel time reliability based on consolidated past research and methodologies. This project's purpose was to further develop and pilot the viability of the options-theoretic approach in Maryland, establish a localized range of reliability values based on state travel time data, compare the new values to those already in use, apply the newly established values in the project development and analysis process, and conduct an assessment of the findings and results. A travel time data-driven methodology was constructed to produce a range of local values for reliability, and the sensitivity of this range of values was examined using an actual short-term congestion relief project to better understand application effects. While the data-driven method shows promise, additional validation is required on the underlying theories, method, and test application results. Suggestions for further research are presented.

In addition, the applicability of incorporating the value of reliability into long-range project development, prioritization, and selection was explored as a proof of concept. Although the Maryland State Highway Administration is the basis for this pilot study, the underlying theory, principles, and data-driven method, as well as the further research suggestions, could be informative to other agencies and jurisdictions that have an interest in considering incorporating travel time reliability into their project development and programming decision-making process.

# CONTENTS

# Executive Summary

The topic of travel time reliability has been a significant focus in the transportation systems management and operations (TSM&O) community during recent years. With the end of the second Strategic Highway Research Program (SHRP 2) Reliability research program in sight, agencies are working to figure out how to incorporate travel time reliability–related performance measures, analytical processes, and tools into their planning and programming processes. Travel time reliability describes the quality, consistency, timeliness, predictability, and dependability of travel. What is occurring today is a fundamental shift from a past policy focus on average travel time to one that now focuses on variability of travel time.

The specific problem that this research project addresses is to identify how an agency can include a value of travel time reliability (VTTR) in a benefit–cost analysis (BCA) when making congestion reduction–related project investment decisions. This project builds on the experiences of the Maryland State Highway Administration (SHA) and their ongoing efforts to include reliability in their planning and programming processes. In recent years, SHA has adopted a reliability performance measure and has included a VTTR in their BCA process when selecting congestion relief projects for implementation. The stated project objectives for this project were as follows:

- Select and defend a value or range of values for travel time reliability for the Maryland State Highway Network.
- Use the VTTR in the Maryland SHA project development process to prioritize operational and capital improvements and determine if (and how) the ranking of projects changes due to the addition of VTTR.
- Report for the benefit of others the step-by-step process used to develop, justify, apply, and assess the use of VTTR in the Maryland SHA project evaluation and decision process.

This research project is presented in two parts. Part 1: Background and Application of the Method provides the results of the project in four chapters: (1) Background, (2) Research Approach, (3) Findings and Applications, and (4) Conclusions and Suggested Research. Part 2: Description of the Method provides an in-depth treatment of the development and application of a travel-time data-driven methodology for estimating value of reliability, including the methodology's assumptions, example application and calculations, and how it attempts to improve on a previous application of Real Options theory.

The following sections provide a synopsis of how each objective was addressed, along with any related findings and products. The final section of the Executive Summary addresses conclusions and recommendations for further research.

## Select and Defend a Value or Range of Values

SHA currently uses a VTTR in their existing life-cycle BCA for congestion relief projects. Following recent trends, particularly in European nations where reliability benefits are accounted for as a percent of congestion reduction–related savings, SHA adds 75% (known as the reliability ratio [RR]) of the congestion-related savings as reliability savings to overall project benefits. This research project demonstrates how this value can be defended by (1) a review of existing literature and (2) a proposed data-driven methodology for determining a new value of reliability (or range of values) using mass quantities of local historical travel time data. Based on the results of (2), new localized values of the reliability ratio were calculated and input into the current life-cycle BCA methodology (as described in the next section).

In the past, two distinct approaches have been used to define travel time reliability for valuation purposes, the first of which is based on behavioral modeling, which has been, by far, the most frequently used approach. Behavioral approaches followed two major paths: (1) statistical methods that directly estimate travel time distributions and variations and (2) survey-based methods based on disaggregate data and discrete choice models. A detailed literature search of these approaches is included in this report. Compared with the recent revealed and stated preference survey-based estimates in the literature, SHA's current use of a reliability ratio of 0.75 seems reasonable and may even be, to some extent, conservative.

The second approach is based on Real Options theory, which has been applied once under SHRP 2 L11: Evaluating Alternative Operations Strategies to Improve Travel Time Reliability. This SHRP 2 L35B research project made a concerted effort to improve on the L11 methodology by building off this previous work, while, at the same time, providing transparency in the newly developed methodology and clearly demonstrating how issues identified in the L11 approach have been addressed. There are three strong reasons for continuing to pursue this approach: (1) it is based on access to historical travel time data, which is becoming more accessible to agencies via contracts with third party probe data providers or the freely available Federal Highway Administration (FHWA)–sponsored National Performance Measures Research Data Set (NPMRDS); (2) because of access to ubiquitous archived travel time data, the methodology is readily implementable by agencies; and (3) it provides a different kind of "tool" for the travel time reliability valuation "tool kit," in addition to the existing behavioral modeling approaches. Challenges remain, particularly in conveying a complex approach in a manner that is relatively intuitive and easy to understand.

In an attempt to make the complex relatively simple, the proposed travel-time data-driven methodology for estimating value of reliability uses large quantities of historical travel time data, along with a value of typical/usual travel time (VOTT, also known as VOT) and produces an RR along with a value of travel time reliability (VTTR, or VOR). A brief summary of the steps involved in the methodology is as follows: First, the appropriate parameters of a stochastic process describing the evolution of travel time observations are calibrated. This stochastic process is used to predict the future distribution of travel time. Then, based on well-established results of other behavioral studies, the predicted late and early arrivals are transformed into equivalent monetary penalty values. The final step is to calculate the current certainty-equivalent expected value of future penalties, which results in the VTTR. Note that, conventionally, the RR is defined as the ratio of VTTR and VOTT.

In providing a high-level explanation of how the methodology works, an analogy is used that is related to the purchase of an insurance premium that guards against the risk of being late. If travelers, based on experience, know that their morning commute to work takes 10 minutes on average, they might be willing to add 5 minutes to their trip time to avoid the risk of being late to work. This extra 5 minutes has a monetary value and represents the insurance premium that the traveler is willing to pay for this trip. The challenge is to determine this value (the extra 5 minutes in this example) using factors such as expected travel time, variations in historical travel time, tolerance of travel time variation, and how differences in expected travel time might impact the travelers' experience.

In practice, the methodology involves the complex application of Real Options theory. Additional detail about the methodology is included in Chapter 3. However, for a detailed in-depth treatment of the methodology's development, its assumptions, example application and calculations, as well as how it improves on the previous application of Real Options theory, refer to Part 2. The methodology uses large quantities of historic travel time data for a trip to (1) calculate the future distribution of travel time and (2) using this future time distribution, apply a recursive process to estimate the present value of reliability.

The proposed data-driven methodology was implemented in Maryland and used to estimate a local value for RR and ultimately a travel time VTTR. The methodology was implemented using MATLAB to automate the process (note that the MATLAB code is provided in Appendix B). A year's worth of archived probe-based travel time data was used to estimate the local RR and VTTR values on five different corridors in Maryland. Results of the data-driven methodology application indicate that the currently used RR of 0.75 is within the calculated range of values for commute trips (0.68 to 0.87).

## Use VTTR in the Maryland SHA Project Development Process

As noted previously, the Maryland SHA has an existing short-term project development process that is focused on congestion relief projects. The details of this process are included in this report, but the high-level steps include

1. Diagnosis. This involves identification of the most unreliable segments of the highway system. SHA uses the planning time index (PTI) (95th percentile travel time) as the reliability performance measure.
2. Analysis. SHA uses an existing 20-year life-cycle BCA analysis for project prioritization. SHA adds 75% of the congestion-related savings as reliability savings to overall project benefits as the value of travel time reliability.
3. Selection. Based on this prioritized list, SHA works with various stakeholders to select projects to program for design and construction.
4. Assessment. Postconstruction reliability improvements are assessed using the planning time index.

Given that the data-driven methodology estimated a range of RR values that could be used to calculate reliability-based savings, a sensitivity analysis was conducted to determine the impact of a range of RR values on congestion relief project selection. This was accomplished by selecting a case study to document how congestion relief projects were prioritized on the Baltimore Beltway (I-695) in 2012. This short-term project improvement selection process focuses on low-cost solutions that exclude major roadway improvements, such as bridge widening and or anything requiring major right-of-way acquisition. A range of reliability ratios was applied to the BCA process used on the Baltimore Beltway to determine how congestion relief project prioritization might change based on changes in VTTR. It was determined that at low budget levels, the choice of RR can be an important factor in project prioritization.

Note that the analysis results obtained from these short-term improvement projects are based on aggregate travel time savings. Therefore, to estimate the VTTR benefits, a constant factor of 0.75 was applied to the reported value of travel time (VOTT) savings. The reader should note that this is an approximation and effectively reflects the implicit assumption that all origin–destination (O-D) pairs affected by the proposed improvements have the same travel times and volumes in before/after scenarios. The research team acknowledges this significant assumption; however, in the absence of detailed O-D information for short-term improvement project analysis (and perhaps in similar practical decision-making scenarios), this exemplifies the versatility of the proposed reliability valuation method.

In addition to short-term congestion relief project selection, the research team looked at the impact of incorporating a value of travel time reliability into long-term project prioritization and selection. This was accomplished using the Maryland Statewide Transportation Model (MSTM), a long-term travel demand model. In this case, disaggregate O-D information is used to estimate VOTT and VTTR savings. The results presented in this report should only be regarded as a proof of concept, as development of the base-year and future-year travel demand models is still in progress. However, this research demonstrates that incorporating travel time reliability valuation into a regional travel demand model can be relatively easy.

## Report the Step-by-Step Process Used by the Maryland SHA

The high-level steps used to incorporate VTTR into the Maryland SHA project evaluation and decision process were as follows.

### Step 1: Document Existing Project Selection Process

This step involved documenting the existing life-cycle BCA process for which VTTR was being used in consideration of prioritizing congestion relief projects for implementation.

### Step 2: Define Trips and Corridors to Be Analyzed

This step involved selecting the routes and corridors connecting major O-D pairs for which a local value of reliability is desired. The selection should be done in conjunction with Step 3 to ensure that the required historical travel time data are available.

### Step 3: Acquire Data to Be Used for Analysis

The Maryland SHA has access to link-based historical travel time data based on vehicle probes [both INRIX and the National Performance Measures Research Data Set (NPMRDS)] for all highways and major arterials. Many departments of transportation across the country are already using vehicle probe–based travel time data.

### Step 4: Calculate RR/VTTR

The research team used the travel-time data-driven methodology for estimating value of reliability developed as part of this project for calculating a local reliability ratio and value of reliability. The methodology used is explained in Chapter 3 as well as in Part 2: Description of the Method. The MATLAB code used to automate this process is included in Appendix B.

### Step 5: Incorporate RR into the Existing Short-Term Congestion Relief Project Selection Process

The local VTTR calculated using the travel-time data-driven methodology for estimating RR/VTTR was used to replace the current value in the baseline approach. The impact of replacing the RR currently used with a range of RRs was analyzed using projects selected in the past as a case study.

### Step 6: Incorporate RR into Long-Term Project Selection Process

This was accomplished using the MSTM, a long-term travel demand model. The results are presented in Chapter 3 of this report, along with details of the process used.

### Step 7: Present to SHA Management

Maryland SHA stakeholders were briefed on project progress throughout the conduct of the research project. The research team was led by a member of SHA's Office of Planning and Preliminary Engineering. A presentation was prepared and made to upper management within SHA to gauge their reaction to the findings of this research. This presentation is summarized at the end of Chapter 3, and the presentation slides used are included in Appendix C.

## Conclusions and Recommendations

An overall conclusion from this research suggests that agencies that do not account for VTTR in their BCA processes are undervaluing project benefits resulting from improvements to trip reliability. Valuation tools and techniques, both existing and newly developed as a result of this research, along with a significant body of literature, provide a basis for incorporating VTTR into an agency's BCA process. While this research project focused on Maryland State Highway as a case study, the information (literature, data-driven methodology, application examples) documented in this report could help agencies looking to incorporate VTTR into their investment decision processes.

Compared with the recent revealed and stated preference survey-based estimates in the literature, the current RR ratio value of 0.75 used by SHA seems reasonable. Based on the development and application of the data-driven approach to reliability valuation methodology developed under this research, it can be concluded that, in Maryland, during peak hours in congested urban areas, the average RR ranges between 0.68 and 0.87, derived from MSTM and Census Bureau travel times, respectively (IndexMundi 2013; U.S. DOT 2013). In nonurban areas and at off-peak hours, the average RR can be taken as 0.52. Therefore, it seems the current value of 0.75 is reasonable when the reliability of commute travel times during peak hours in congested urban areas is considered. Note, however, that while this value appears reasonable based on the application of the newly developed data-driven reliability valuation methodology, the results obtained under this research do not necessarily validate this value because the data-driven valuation methodology itself must be validated. Future research identified in Chapter 4 of this report will facilitate methodology validation. The reader is also cautioned that this ratio can differ based on transportation facility type, mode, level of congestion, vehicle fleet composition, time of day, trip purpose, and so forth. Estimates of the value of reliability may be modified when these factors are taken into consideration.

Given that the Maryland SHA is able to account for the benefit of project-related travel time reliability improvements, a potential next step is to incorporate the results of this project into a future iteration of the Maryland State Highway Mobility Report in the form of costs due to unreliability. Currently, the report includes performance measures based on congestion (travel time index) and reliability (planning time index). While the statewide cost of congestion is reported, an estimate of the additional cost users incur as a result of a lack of reliability in travel times, and as measured and reported using the planning time index, is not currently included. The VTTR estimates obtained from this research can now be used to bridge the gap in reporting costs of unreliability in the annual Mobility report.

As noted above, Part 1 of this report can help agencies incorporate VTTR in their investment decision processes. Every effort has been made to fully document the data-driven valuation methodology developed under this research to facilitate its transferability to agencies beyond the Maryland SHA. However, doing so at this time would likely require teaming with a university or consultant. A logical next step that would facilitate transferability among agencies, and overall ease of implementation, would be to develop (or build into an existing performance-measure calculation and reporting tool) a software tool that can process the historical travel time data and estimate RR/VTTR using the methodology developed. In addition to this suggestion of follow-on work to facilitate the practical application of the results of this research, ideas for future research to build on and enhance the developed data-driven methodology are included in Chapter 4.

PART 1

# BACKGROUND AND APPLICATION OF THE METHOD

CHAPTER 1

# Background

## Introduction

The topic of travel time reliability has been a significant focus in the transportation systems management and operations (TSM&O) community during recent years. With the end of the Strategic Highway Research Program (SHRP 2) Reliability research program in sight, agencies are working to figure out how to incorporate travel time reliability–related performance measures, analytical processes, and tools into their planning and programming processes. Travel time reliability describes the quality, consistency, timeliness, predictability, and dependability of travel. What is occurring today is a fundamental shift from a past policy focus on average travel time to one that now focuses on variability of travel time.

The specific problem that this research project addresses is to identify how an agency can include a value of travel time reliability (VTTR) in a benefit–cost analysis (BCA) when making congestion reduction–related project investment decisions. This project builds on the experiences of the Maryland State Highway Administration (SHA) and their ongoing efforts to include reliability into their planning and programming processes. In recent years, SHA has adopted a reliability performance measure and has included a VTTR in their BCA process when selecting congestion relief projects for implementation. The stated objectives for this project were as follows:

- Select and defend a value or range of values for travel time reliability for the Maryland State Highway Network.
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- Report for the benefit of others the step-by-step process used to develop, justify, apply, and assess the use of VTTR in the Maryland SHA project evaluation and decision process.

Part 1 is organized as follows:

- Chapter 1 provides a literature review of previous approaches to reliability valuation and focuses on whether or not, based on the existing literature, the use of 0.75 as a reliability ratio by SHA is defensible.
- Chapter 2 describes the research approach.
- Chapter 3 describes and presents the research findings and applications resulting from this project.
- Chapter 4 provides conclusions and suggestions for future research.

## Previous Approaches to Reliability Valuation

The literature review presented herein aims at using the results of various research studies conducted in the United States and elsewhere for both creating a benchmark for the data-driven approach and for reevaluating the current reliability ratio of 0.75 in use by SHA. First, various methods used in the literature to determine the values of travel time (VOTT) reliability are summarized. Second, values of travel time reliability or reliability ratios (RRs) or ranges of ratios are summarized. Finally, putting the use of these research results into practice by local agencies is discussed and recommendations are made.

In travel time reliability literature, two distinct approaches have been used to define travel time reliability for valuation purposes (Cambridge Systematics and ICF International, 2012): behavioral modeling approaches and an approach based on Real Options theory (a review of the literature on Real Options theory is included in Part 2: Description of the Method). With one exception, all studies in the reliability literature used a behavioral approach in some form. The exception, Evaluating Alternative Operations Strategies to Improve Travel Time Reliability, used an options-theoretic approach (SHRP 2 L11, 2012). The SHRP 2 L11 project was the first to use an options-theoretic approach for determining the value of travel time reliability by using speed and volume data as input. The options-theoretic approach introduced by the SHRP 2 L11 uses an analogy where premiums are set for an insurance policy on guaranteed speed levels. Specifically, the method calculates the dollar value of reliability by multiplying the certainty-equivalent penalty (measured in minutes-per-mile and obtained by applying the closed form Black-Scholes equation) by the value of time, thus it requires an estimation or adoption of VOTT as input. The SHRP 2 L11 study takes into account heterogeneity of the road users and different trip purposes by applying a separate value of time that corresponds to each user group.

Use of an options-theoretic approach in transportation under SHRP 2 has led to significant discussion in the research arena by bringing a novel, data-driven approach to travel time reliability valuation. The discussions included some questioning of the assumptions and methods used. The most significant question was with regard to the use of speed as a measure to set an insurance policy premium on guaranteed speed levels. The issue is, given speed is a measure that is not directly related to travel cost it cannot be discounted in the same way that financial analysts discount money. Another significant question relates to the assumption of the lognormal distribution for speed variation; it does not address situations where speed/travel time is not distributed lognormally. Thus, the method used in SHRP 2 L11 is applicable only under a lognormal speed variation assumption. The research team conducting this project studied the questions resulting from the SHRP 2 L11 and attempted to clearly address these questions in its development of a new proposed data-driven methodology using an options-theoretic approach (see Part 2).

Behavioral approaches followed two major paths: (1) statistical methods that directly estimate travel time distributions and variations, and (2) survey-based methods based on disaggregate data and discrete choice models. Among the two statistical methods used to determine the VTTR, the first method uses a mean-variance approach which involves calculation of statistical measures to separate out the VOTT and VTTR. The second method is based on the schedule-delay concept, which focuses on the magnitude of the time encompassing both early and late arrivals in relation to a predetermined schedule. The mean-variance approach is easy to implement but has some theoretical drawbacks, since there is concern about double counting benefits. Double counting occurs if overall mean time is used to represent travel time (for the VOTT), since the mean time includes a portion of the variability component. The schedule-delay approach is conceptually more appealing, but it is more difficult to implement since it requires schedules of individual travelers and the distribution of their associated travel times. There are also methods that combine both mean-variance and schedule-delay methods, but they are more complicated to apply due to extensive data requirements that are not readily available.

Survey-based methods, based on discrete choice models, typically use survey data in the form of stated preferences (SP) or revealed preferences (RP). Carrion and Levinson (2012) provides a comprehensive overview of the major behavioral approaches and evidence gathered over the years regarding the value of travel time reliability. Cirillo et al. (2014) provides a detailed review of behavioral approaches in the context of congestion pricing, including a systematic review of methodologies, interpretations, findings and empirical applications on VOTT and VTTR estimations. After analyzing 14 congestion-pricing examples focusing on travel time reliability, they found that these two methods, survey-based and statistical, are the main research directions in the literature from a congestion-pricing context. Among the proposed survey-based methods, none of them were clearly superior to others. The analyses in the literature are often based on statistical methods and are based on the mean travel time and its variance while reliability is described using buffer indices and planning indices. However, these studies usually involved complications due to the unknown theoretical distribution of travel time, which made comparisons of different studies impossible. For a meaningful universal comparison, the specific characteristics of the travel time distribution are needed.

Much of the past research focuses on estimating VOTT rather than VTTR due to the complexity and difficulty of estimating VTTR (see Table 3 in Cirillo et al., 2014). As an alternative, a typical approach is to use the reliability ratio (RR) (the ratio of VTTR divided by VOTT) as a convenient measure of travel time reliability for project evaluation purposes. An established RR along with knowledge of the VOTT simplifies the task of VTTR estimation. However, previous studies in the United States and elsewhere have shown that RR values vary significantly across different studies. Table 1.1 summarizes the average RR values and their ranges (minimum and maximum) found in previous studies. Note that the studies included in Table 1.1 are built on two previous studies: Carrion and Levinson (2012) and Cambridge Systematics and ICF International (2012).

All of these studies in Table 1.1 used a survey-based behavioral approach, the majority of which are based on SP data or a combination of SP and RP data. There appears to be a lack of consistency in the values estimated, and average RR values vary significantly within and across studies from 0.1 to 2.51. The table shows that the most recent RR values, and 17 out of 25 average RR values, are higher than SHA's current value of 0.75. It is worth noting that recent studies have used RP data. However, it should also be noted that RP and SP results are shown to differ significantly in the literature (Ghosh, 2001; Yan, 2002): RP estimates of VOTT and VTTR are almost double the median estimates of SP. Similarly, Shires and De Jong (2009) also showed that SP and joint SP and RP studies result in significantly lower VOTT savings. In addition to data

*Table 1.1. Value of Reliability for Automobile Travel from Past Research*

| No. | Study | Method | Average RR | Minimum | Maximum | Reliability Metric/Definition |
|---|---|---|---|---|---|---|
| 1 | Black and Towriss (1993) | SP | 0.55 | — | — | Standard deviation |
| 2 | Senna (1994) | SP | 0.76 | — | — | Standard deviation |
| 3 | Small et al. (1995) | SP | 2.30 | 1.31 | 3.29 | Standard deviation |
| 4 | Koskenoja (1996) | SP | 0.75 | 0.33 | 1.08 | Average schedule delay (late and early) |
| 5 | Small et al. (1999) | SP | 2.51 | 1.86 | 3.22 | Standard deviation |
| 6 | Ghosh (2001) | SP and RP | 1.17 | 0.91 | 1.47 | 90–50 Percentile |
| 7 | Yan (2002) | SP and RP | 1.47 | 0.91 | 1.95 | 90–50 Percentile |
| 8 | Brownstone and Small (2005) | SP and RP | 1.18 | — | — | 90–50 Percentile |
| 9 | Liu et al. (2004) | RP | 1.73 | — | — | Median and the 80–50 percentile differences |
| 10 | Small et al. (2005) | SP and RP | 0.65 | 0.26 | 1.04 | Ratio of standard deviation to mean |
| 11 | Tseng et al. (2005) | SP | 0.5 | — | — | Scheduling approach; difference between early/late arrival time and preferred arrival time |
| 12 | Bhat and Sardesai (2006) | SP and RP | 0.26 | — | — | Scheduling approach; standard deviation |
| 13 | Hollander (2006) | SP | 0.10 | — | — | Scheduling approach; mean-variance approach |
| 14 | Liu et al. (2007) | RP | 1.30 | 0.71 | 2.39 | 80–50 percentile |
| 15 | De Jong et al. (2007) | SP | 1.35 | 0.74 | 2.4 | Standard deviation |
| 16 | Asensio and Matas (2008) | SP | 0.98 | — | — | Scheduling approach; standard deviation |
| 17 | Borjesson (2009) | SP | 0.87 | 0.48 | 1.27 | Ratio of sensitivity to standard deviation to sensitivity of the mean |
| 18 | Fosgerau and Karlström (2010) | RP | 1.0 | — | — | Standard deviation |
| 19 | Tilahun and Levinson (2010) | SP | 0.89 | — | — | Scheduling approach; difference between actual late arrival and usual travel time |
| 20 | Li et al. (2010) | SP | 0.70 | 0.08 | 1.59 | Scheduling approach; standard deviation |
| 21 | Carrion and Levinson (2010) | RP | 0.91 | 0.47 | 1.20 | 90–50 percentile |
| 22 | Carrion and Levinson (2011) | RP | 0.91 | 0.69 | 1.12 | Standard deviation |
| 23 | SHRP 2 C04 (2013a) | RP | 1.0 | 0.5 | 1.5 | Standard deviation per unit distance |
| 24 | SHRP 2 L04 (2013b) | RP | 1.63 | 0.57 | 2.69 | Standard deviation per unit distance |
| 25 | Significance et al. (2013) | SP | 0.6 | 0.4 | 1.1 | Standard deviation |

Note: — = not reported; SP = stated preferences; RP = revealed preferences.

sources (i.e., RP versus SP), these values show significant variation depending on the reliability measures used and modeling approach (e.g., heterogeneity, travel time unit, and choice dimensions considered).

The most recent survey-based study to estimate social-economic values of travel time reliability was conducted by Significance et al. (2013) under the supervision of the KiM Netherlands Institute for Transport Policy Analysis for the Directorate-General of the Ministry of Infrastructure and the Environment. Previously, valuation of travel time reliability was determined based on the findings of an international expert meeting, organized by the Dutch Ministry of Public Works, Transport and Water Management. The Dutch values were last estimated in 1997 for passengers and in 2004 for freight transportation using major empirical research studies. The VOTT, VTTR, and RR values were updated annually in line with inflation and wage developments so that they could be used in benefit–cost analyses conducted for infrastructure projects. The Significance et al. (2013) study was the Netherlands' first study to determine the social-economic values for travel time reliability based on empirical research (SP data).

The data collection (SP) for passenger travel and transport was conducted in two steps: in the first survey, 240,000 participants were recruited from the largest online panel (PanelClix)

*Table 1.2. Estimated VOTT, VTTR, and RR for Car Mode by Trip Purpose (in Euro/Hour per Person, Market Prices, Price Level 2010)*

| Trip Purpose | VOTT | VTTR | Reliability Ratio |
|---|---|---|---|
| Home-to-work | 9.25 | 3.75 | 0.4 |
| Business | 26.25 | 30.00 | 1.1 |
| Other | 7.50 | 4.75 | 0.6 |
| Average[a] | 9.00 | 5.75 | 0.6 |

[a] Weighting is based on the division of the trip purposes in minutes traveled, derived from Onderzoek Verplaatsingen in Nederland (OViN) 2010.

in the Netherlands, which led to 5,760 respondents. In the second survey, 1,430 respondents were recruited in the same manner as for the previous research study; namely, at petrol stations along the motorways, parking garages, train stations, tram and bus stops, airports (Schiphol and Eindhoven), and marinas (recreational navigation). For freight transport, face-to-face interviews were held with 812 respondents.

The Significance et al. (2013) study determined VOTT, VTTR, and RR values both for passenger modes (including car, bus, tram, metro, train, airplane, and recreational navigation) and freight modes (including road, rail, inland waterways, sea, and air). The study is significant in the sense that the values of travel time for aviation (based on empirical research) and for recreational navigation were determined for the first time in the reliability literature. The new values are summarized in Table 1.2 (only passenger values are included in the table as other modes are not in the scope of this project).

The Netherlands' values in Table 1.2 are the result of the latest international work; however, other countries have also used either an estimate of their own or an adopted value for travel time reliability for benefit–cost analysis. The latest values estimated in the Netherlands and the values used by other countries are presented in Table 1.3. These values are compiled from various presentations from the International Meeting on Value of Travel Time Reliability and Cost-Benefit Analysis (15–16 October 2009, Vancouver, Canada). Table 1.3 also shows significant variation in RR values in different countries as well. With the exception of the Netherlands' updated values, they all are higher than SHA's current 0.75 value, and even as high as 20 in France. The relatively low values of RR in the Netherlands is attributed to behavioral changes over time resulting from, for example, increased use of travel time by means of technological advances and methodological refinements in estimating these values.

Given the significant variation in reliability ratios in the existing literature, the Maryland SHA and the research team chose an approach to estimate a new RR (or range of values) using available local travel time data. The proposed data-driven methodology using an options-theoretic approach developed under this project provides a VTTR for SHA based on readily available local travel time data.

## Applying VTTR in Decision Making

Prior to the SHRP 2 Reliability effort that started in 2009, no research existed for estimating reliability metrics based on the travel time distribution. These earlier works distinguished between recurring and nonrecurring delay (typically defined as incident delay), and then used nonrecurring delay as an indicator of reliability.

Dowling developed a method for estimating recurring and nonrecurring delay for the California Department of Transportation (Caltrans) based on a probability tree to predict the expected number and duration of incidents (Dowling et al., 2004). The method is designed for application to a few selected facilities in a district and the results extrapolated to

*Table 1.3. RR Values for Cost–Benefit Analysis in Other Countries*

| Country | Reliability Ratio (RR) |
|---|---|
| The Netherlands (Significance et al., 2013) | 0.6 for auto and public transit (min 0.4, max 1.1) (old values 0.8–1.4 for personal auto and public transit, respectively) |
| New Zealand (Taylor, 2009) | 0.8 for personal autos |
| Australia (Taylor, 2009) | 1.3 for personal autos |
| Sweden (Eliasson, 2009) | 0.9 for all trip types |
| Canada (Cambridge Systematics and ICF International, 2012) | 1.0 for all trip types |
| UK (Department for Transport, 2014) | 0.8 for highways, 1.4 for transit |
| France (Delache, 2009) | 2 to 20 for auto, 6 for transit |
| Japan (Fukuda, 2009) | 0.966 for all trip types |

Note: The United Kingdom uses values estimated by the Netherlands, so these values may have been updated accordingly.

obtain district totals. The recurrent and nonrecurrent delays for each sample facility are computed for three prototypical days (weekday, weekend, holiday) in each of the four seasons of the year (winter, spring, summer, fall). The delays computed for each prototypical day are factored to seasonal totals according to the number of days that each day represents of each season. The seasonal totals are then summed to obtain annual totals. The method requires geometric data, demand data, collision history, frequency of maintenance and construction activities, frequency of inclement weather days, and frequency of special events. Default parameters and distributions are provided for use when local data are not available.

The University of Florida developed a series of simple predictive equations for total travel time based on binary combinations of conditions (present/not present) for congestion, incidents, weather, and work zones (University of Florida, 2007). The analyst estimates the probability of each combination occurring, and a weighted total travel time is computed. This method is currently being adapted for statewide use by the Florida Department of Transportation.

The University of Maryland, as part of the ongoing Coordinated Highways Action Response Team (CHART) evaluations conducted for the Maryland SHA, developed a predictive equation model based on running experiments with microscopic simulation. Cambridge Systematics also developed a set of predictive equations for predicting recurring- and incident-related delay using a stochastic approach that varied both incident characteristics and demand levels. This procedure was adopted for use by FHWA's Highway Economic Requirements System (HERS) model.

This same approach was also used by Cambridge Systematics to develop incident delay relationships for the Intelligent Transportation Systems Deployment Analysis System (IDAS) model (FHWA, 2014). In both the HERS and IDAS models, recurring and incident delay are assigned monetary values. Recurring delay is valued at a rate established by U.S. DOT (TransportationEconomics.org, 2010). Incident delay is valued at twice that rate, but the basis for the valuation is from older studies prior to 1999 (Cohen and Southworth, 1999).

For the Integrated Corridor Management program, Cambridge Systematics developed a scenario-based approach for use with microscopic simulation models, for analysis at a corridor level (Cambridge Systematics, 2008). The scenarios are primarily based on combinations of demand level and incident characteristics. Empirical data are used to estimate the probability of each scenario occurring, and the results of each simulation are combined via weighting.

The Second Strategic Highway Research Program (SHRP 2) was authorized by the U.S. Congress to address the nation's most pressing needs related to the highway system: safety, renewal, reliability, and capacity. The SHRP 2 Reliability focus area has been the driver of research in this area since the onset of the program and is the main focus of the remainder of this literature review. SHRP 2 reliability research has focused mostly on reducing congestion through incident reduction, management, response, and mitigation by developing basic analytical techniques, design procedures, and institutional approaches to address the events that make travel times unreliable (TRB, 2014). Among more than 25 research projects under the Reliability focus area, only a few of them address the estimation of value of travel time reliability. There are also few research projects under the Capacity focus area that also address estimating value of reliability.

One of the most comprehensive SHRP 2 projects that address inclusion of reliability in travel demand models is under the capacity program SHRP 2 C04, Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand (SHRP 2 C04, 2013a). The SHRP 2 C04 project aimed to synthesize past research on understanding and predicting changes in travelers' behavioral response to changes in traffic congestion and travel price. Their synthesis is used to (statistically) test selected behavioral hypotheses on suitable data obtained from around the United States. In addition, the research provided guidelines for incorporating developed functions into existing travel demand and network simulation models. Although the C04 research is under the SHRP 2 Capacity Research Program, it involves building mathematical models of highway user behavioral responses to travel time reliability in addition to congestion and pricing. The values of travel time and travel time reliability are considered among the factors that affect traveler demand and route choice behavior. Other factors considered include demographic characteristics, car occupancy, situational variability, and an observed toll aversion bias.

The SHRP 2 C04 study estimates various highway utility functions and finally suggests the use of the function given below:

$$U = \Delta + a_1 \times \text{Time} \times (1 + a_2 \times D + a_3 \times D^2) + b \times [\text{Cost}/(I^e \times O^f)] + c \times (\text{STD}/D)$$

where

- $\Delta$ = alternative-specific "bias" constant for tolled facilities;
- $a_1$ = basic travel time coefficient, ideally estimated as a random coefficient to capture unobserved user heterogeneity;
- Time = average travel time;
- $D$ = travel distance;
- $a_2$, $a_3$ = coefficients reflecting the impact of travel distance on the perception of travel time;
- $b$ = auto cost coefficient;
- Cost = monetary cost including tolls, parking, and fuel;
- $I$ = (household) income of the traveler;
- $O$ = vehicle occupancy;

$e, f$ = coefficients reflecting the impact of income and occupancy on the perception of cost respectively;

STD = day-to-day standard deviation of the travel time; and

$c$ = coefficients reflecting the impact of travel time (un)reliability.

The SHRP 2 C04 team tested various functional forms for representing the reliability effect, including standard deviation in day-to-day time, the difference between the 90th and 50th percentile times, and the difference between the 80th and 50th percentile times. The measure that produced the most consistent results was the standard deviation in travel time divided by journey distance. Thus, the suggested main measure of travel time reliability is specified as the day-to-day standard deviation of the travel time by auto, divided by distance. This measure has some advantages: (1) avoids the problem of having correlation between travel time, travel cost, and any travel reliability measure including standard deviation or buffer time, and (2) a plausible behavioral interpretation that travelers may perceive travel time variability as a relative (qualitative) measure rather than absolute (quantitative) measure.

This form of highway utility function used in the SHRP 2 C04 project report allows for deriving VOTT and VTTR as follows:

$$\text{VOTT} = (a_1/b) \times (1 + a_2 \times D + a_3 \times D^2) \times (I^e \times O^f)$$

$$\text{VTTR} = \frac{c}{b} \times \frac{(I^e \times O^f)}{D}$$

VOTT can be derived as a function of travel distance, income, and car occupancy for each travel segment.

Similar to VOTT, VTTR also is a function of travel distance, income, and car occupancy for each travel segment unless a more detailed explicit segmentation is applied. Note that VTTR is inversely proportional to distance. However, as the travel distance increases, travel time variations dampen in a relative sense. Finally, the reliability ratio was calculated as a measure of the relative importance of reduction of (un)reliability versus average travel time savings as follows:

$$\text{RR} = \frac{\text{VTTR}}{\text{VOTT}} = \frac{c}{a_1} \times \frac{1}{(1 + a_2 \times D + a_3 \times D^2) \times D}$$

The SHRP 2 C04 project estimated VTTR and VOTT simultaneously using real-world data from actual traveler choices (RP data). The study results suggest that improvements in travel time reliability are at least as important as improvements in average travel time. The reliability ratio for auto travel is estimated to be between 0.7 and 1.5 for various model specifications, and it is following an increasing trend based on the results from other research. These results are in line with previous research results, most of which are based on SP studies from Europe. Typical values for auto travel are in the same range, while values for rail and transit can go up to 2.5. The results obtained from the SHRP 2 C04 project are significant in the sense that they reflect the actual choices of users, while SP based study results may vary significantly, as the previously described Carrion and Levinson (2012) review study presents, depending on how the reliability concept is presented to respondents in the hypothetical scenarios.

The SHRP 2 C04 results indicate that the traveler's value of travel time and value of travel time reliability changes by origin–destination (O-D) trip distance as well. Travelers value savings on average or typical travel time more highly for longer trips than for short trips, except for very long commuting trips (over 40 mi). The value of reliability also shows a relative damping effect for longer trips.

The SHRP 2 C04 study results indicate that incorporation of the reliability models into travel demand forecast models will need further research, particularly regarding collection of actual O-D level travel time variability data. Also, the network simulation models need to be extended to incorporate travel time reliability in route choice and to generate O-D travel time distributions ("reliability skims") instead of average travel times. Because the study found the variation of VOTT and VTTR by trip distance, using different VOTT and VTTR by different trip types will be necessary instead of assuming a constant for a wide range of short and long trips as is pertinent to most travel models currently.

SHRP 2 projects such as L04, Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools, and C10, Partnership to Develop an Integrated, Advanced Travel Demand Model and a Fine-Grained, Time-Sensitive Network, aimed at closing these gaps. The methods developed in C04 can be applied for corridor-level or facility-level forecasts while research is still ongoing on the modeling side (SHRP 2 L04, 2013b, and SHRP 2 C10, 2010a). SHRP 2 C04 also suggests that some simplified proxy measures of reliability, such as perceived highway travel time by congestion levels, can be applied to the existing traditional (static) model structures. The perceived travel time concept uses the notion that highway users driving in congested conditions might perceive the longer travel time as an additional delay or penalty on top of free-flow (or some expected) time (SHRP 2 C04, 2013a). It can be represented by segmenting travel time coefficients by congestion levels in the highway utility function. This would result in a larger disutility associated with congestion. The perceived travel time concept provides an operational proxy for a reliability measure where obtaining an explicit reliability measure is not feasible or possible. Perceptions of travel time by congestion levels can be obtained by traditional network simulation models. The required level-of-service (LOS) skims can be generated by static assignment methods, while advanced methods such as Dynamic Traffic Assignment (DTA) can be more beneficial, or rather necessary, as stated in Chapter 3 of the SHRP 2 C04 draft report:

> It is important to note that making this approach operational within the framework of regional travel models requires explicitly deriving these measures from simulation of travel time distributions, as well as adopting assumptions regarding the ways in which travelers acquire information about the uncertain situation they are about to experience. DTA and traffic microsimulation tools are crucial for the application of models that include explicit travel time variability, since static assignment can only predict average travel times.

The methodology presented in the SHRP 2 C04 project is sound but requires extensive survey and modeling work. Even applying the suggested proxy approach with traditional models would require significant effort while not necessarily providing the desired accuracy in measuring reliability. Therefore, it is not easily applicable for many agencies due to the required level of data and modeling efforts.

SHRP 2 C11, Development of Tools for Assessing Wider Economic Benefits of Transportation (SHRP 2 C11, 2010b), can be thought of as a simpler solution to the issues presented thus far. The C11 project aims to help planners in conducting impact assessment of transportation capacity projects on conditions that directly affect wider economic benefits. In this project, a value of travel time reliability is not estimated but a range of values of reliability ratio obtained from the literature are used to demonstrate calculation of the economic benefit of travel time reliability savings. The default reliability ratio used in the tool was 0.8 for personal travel, based on SHRP 2 L04 report (2013b), and 1.16 for commercial travel.

In SHRP 2 C11, four tools are developed that provide measuring of impacts on travel time reliability, market access, and intermodal connectivity. These three metrics are incorporated in an accounting system of economic benefit and economic impact analyses. The economic benefit and impact analysis tool is freely available as a Microsoft Excel spreadsheet. The advantage of the tool is the simplicity of data requirements that can easily be collected or obtained. The tool can also be used in conjunction with travel models, land use models, or economic models, if desired.

The Puget Sound Regional Council (PSRC) incorporated reliability directly in their travel demand model, using principles established in the SHRP 2 C11 project. This essentially amounts to a shifting of the speed-flow curves to the left, to account for the extra "impedance" caused by unreliable travel (i.e., nonrecurring congestion sources).

The tool developed in the SHRP 2 C11 project can readily be used by many agencies for conducting impact assessment of transportation capacity projects considering reliability of travel time as well. However, the C11 project does not provide a method or tool to estimate value of reliability but requires using a value obtained from either the literature or survey data.

The SHRP 2 L05 project, Incorporating Reliability Performance Measures into Transportation Planning and Programming Processes (SHRP 2 L05, 2013c), looked at using previous research in transportation planning and programming processes by providing agencies guidance in incorporating reliability into their planning and programming processes. The project produced three reports: (1) a guide, (2) a technical reference, and (3) a final report to guide agencies on incorporating reliability into their transportation planning and programming processes. This project also did not include estimating value of reliability but rather focused on (1) measuring and tracking reliability performance, (2) incorporating reliability in policy statements, (3) evaluating reliability needs and deficiencies, and (4) using reliability performance measurement to inform investment decisions. These four main steps are explained in detail in the guide. The technical reference provided detailed descriptions of available analytic tools. The final report summarized all the research conducted, including validation of case studies. In these case studies, the L05 project team used a reliability ratio range of 0.9 and 1.25. The SHRP 2 L05 project team also developed a spreadsheet and variants, which were used to support calculations that were used in the case studies.

## Summary and Conclusions

The value of reliability is disaggregate in nature and varies across individual travelers, by trip purpose, by trip distance, by trip time of day, by mode, and by many other possible factors. Using a reliability ratio without establishing empirical values from locally collected data implies that the value of reliability is a function of the value of average travel time and assumes the same for all travelers, trip purposes, time of day, and so forth. This is a strong assumption, and the use of a single value makes it even stronger. However, establishing a value for travel time reliability or a reliability ratio with widely used methods (i.e., survey-based behavioral methods) is expensive and time-consuming due to extensive data collection requirements. Since these VTTRs and RRs are built on survey data, it is also difficult and costly to update them or generalize them because they likely are not transferable. Moreover, they are not perfect, either; in addition to data-related issues, they are vulnerable to modeling assumptions, simplifications, and errors.

As discussed in this chapter, reliability ratios that are found in the literature are very different and subject to the specific characteristics of each study. Therefore, using a single VTTR or RR will likely be misleading. A methodology to establish values of reliability that are generally accepted and applicable with relative ease has yet to be developed. Therefore, it is recommended that a range of values be used in the absence of empirical data and sources to estimate them.

Based on the literature, the dispersion among RR estimates from stated preference surveys is considerably larger than the RR estimates from revealed preference surveys. The latest revealed preference survey reports an average RR estimate of 0.91 (Carrion and Levinson, 2012), while the most recent stated preference survey (Significance et al., 2013) reports an average 0.60 RR estimate for all highway trip purposes.

Compared with the recent revealed and stated preference survey-based estimates in the literature, SHA's current RR value of 0.75 seems reasonable and may even be, to some extent, conservative. For instance, according to Concas and Kolpakov (2009), VTTR varies between 80% and 100% of VOTT in ordinary/everyday conditions (no major constraints). They also claim that VTTR can be up to three times the VOTT in instances where nonflexible arrival/departure constraints exist. Therefore, the adopted RR estimate in Maryland needed further detailed analysis based on local conditions and available data. As noted previously, the proposed data-driven methodology using an options-theoretic approach developed under this project provides a VTTR for SHA based on readily available local travel time data.

Incorporating reliability into decision making requires data on existing travel time reliability and a measure of reliability, forecasting the reliability level after a project or policy is implemented (thus a method for predicting future reliability), and monetary values of reliability disaggregated at the appropriate level of detail. Most these requirements, particularly forecasting future reliability, need further research. Besides, most of the existing research has been mainly focused on passenger transport, and research is needed for other modes, especially for areas with multimodal networks and significant freight corridors such as Maryland (International Transport Forum, 2012).

CHAPTER 2

# Research Approach

Through the adoption of various measurement and reporting methodologies and tools, Maryland State Highway Administration (SHA) has been able to quantify current mobility and reliability conditions and trends on its highways. This provides a basis for examining how those variables change with the evolving transportation environment, and to assess how the agency's actions can efficiently impact the users of the state's transportation system. This also gives the Maryland SHA the ability to develop better informed decisions regarding the use of its limited resources, identify critical transportation issues before they develop into more serious problems, and provide measurement of its success.

## Describe SHA's Established Processes

The Maryland SHA has a life-cycle benefit–cost analysis (BCA) process in place to identify and prioritize improvements. The research team held multiple meetings with SHA planning staff to document SHA's baseline process. The baseline process was documented in the context of recent project evaluations performed by the agency so that the existing project prioritization and selection process could be used as a case study. It should be noted that while many planning and project programming processes exist within SHA, the research team focused on the existing congestion relief project selection process as this is where SHA is already applying both a reliability-based performance measure and value of travel time reliability. The research team paid special attention to note how the value of travel time is already established in the baseline approach.

## Identify and Acquire Data Needed to Perform Research

SHA has procured INRIX-based vehicle probe data sets for the entire state, which provide speed information at 15-, 5-, and 1-minute intervals. This data set augments the real-time freeway data SHA already receives from INRIX through the Regional Integrated Transportation Information System (RITIS). RITIS is an automated data sharing, dissemination, and archiving system housed at the University of Maryland's Center for Advanced Transportation Technology (CATT) Laboratory. SHA uses this archived data along with other data for performance measurement, congestion, and reliability analysis of its transportation infrastructure.

Using INRIX-based vehicle probe data, SHA has developed congestion and reliability-related measures [travel time index (TTI) and planning time index (PTI)] on all the freeways and expressways in Maryland. From a congestion standpoint, two major measures of highway performance are: (1) percent system congested during peak hours; and (2) percent of vehicle miles traveled (VMT) in congested conditions during peak hours. Vehicles traveling at 70% of free-flow speed (equivalent to TTI of 1.3) on a freeway are considered to be experiencing congestion. Level of congestion varies from light to moderate to severe. Similarly, depending on the PTI, segments of freeways are considered as highly unreliable, moderately unreliable, and reliable. Findings of these analyses have been summarized in recent reports on the status of mobility in the state of Maryland (Maryland SHA, 2012).

## Identify Method to Forecast Future Travel Time Reliability Measures

The Maryland Statewide Transportation Model (MSTM) is a long-term travel demand model developed by the National Center for Smart Growth Research and Education (NCSG) at the University of Maryland (National Center for Smart Growth and Parsons Brinckerhoff, 2011). This model covers transportation and land use activities at three distinct layers: national, statewide, and Metropolitan Planning Organizations (MPOs). Figure 2.1 illustrates the four-step modeling approach undertaken by MSTM to model person (outlined with red dots) and

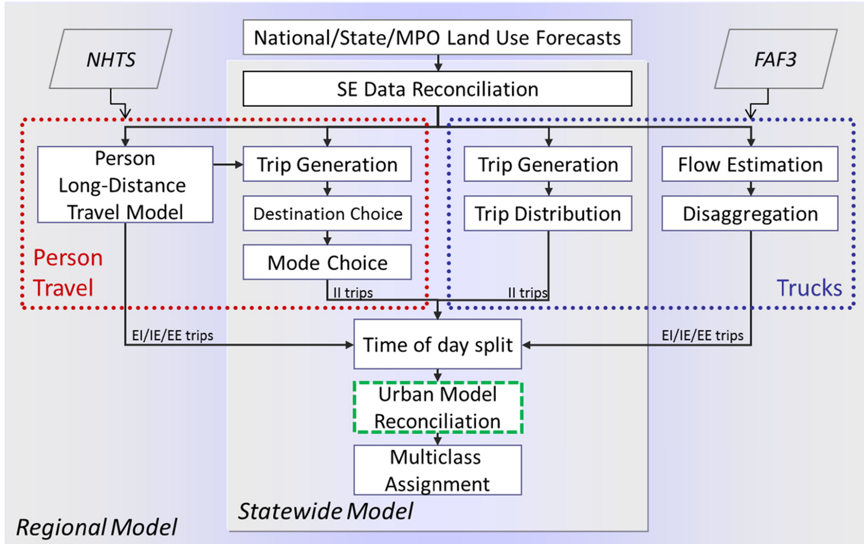



***Figure 2.1. Overview of MSTM—Phase 3. (II = internal to internal; EI = external to internal; IE = internal to external; EE = external to external.)***

truck travel (outlined with blue dots). In the MSTM framework, it is possible to incorporate travel time variability measures into the utility of mode and route choice alternatives between each origin–destination (O-D) pair. MSTM is a functional travel demand model currently used for a number of practices at SHA.

In addition, NCSG researchers are currently enhancing MSTM by incorporating a Dynamic Traffic Assignment (DTA) capability. Chapter 3 identifies how MSTM was used to explore the impact of incorporating the value of travel time reliability into long-term project prioritization and selection decisions.

## Calculate a Local Value of Travel Time Reliability

Ultimately, the research team chose to focus on building off previous work on an options-theoretic approach to determine VOTT and VTTR analytically. The reliability ratio (RR) is a convenient way of estimating VTTR for project evaluation purposes. While Chapter 3 provides an overview of the proposed travel-time data-driven methodology for estimating value of reliability, Part 2 of the report provides an in-depth treatment of the methodology's development, its assumptions, example application, and calculations, as well as how it tries to improve on the previous application of Real Options theory. The proposed method is data driven and requires access to fine granularity and long-term archived travel time data. This method is based on the analogy of an insurance policy designed to cover travelers against the negative impacts of unexpected variations in travel time. The proposed method has been designed to provide maximum flexibility for valuing travel time reliability based on existing local information and experiences. A review of the previous attempt to apply Real Options concepts to the problem of travel time reliability valuation is provided. Reasons as to why the previous attempts have received a cautious review are explained. Also, Part 2 sets out to unravel some of the less clear aspects of the previous work by venturing further into the nuts and bolts of the approach and clearly identifying the distinctions between the proposed method and the earlier effort.

Part 2 also includes a brief background on classical utility theory and its application in travel time reliability valuation. Strengths and limitations of utility-based estimation methods are discussed. A travel time insurance analogy is adopted to illustrate the different aspects of the proposed approach. Setting a premium on the proposed travel time insurance is presented and discussed in the context of options-theoretic valuation and asset pricing. Examples are provided throughout the technical report to facilitate the discussions and to demonstrate application of the concepts. Applications of the proposed methodology using a year's worth of travel time data in the state of Maryland are reported. Analysis performed on the results of this application are presented and models to relate the travel time reliability ratio and average travel time (as well as 95th percentile travel time and average travel time) are calibrated.

Finally, Part 2 includes two appendices. Appendix D provides a brief review of stochastic processes, and in particular, the geometric Brownian motion (GBM) process including its properties and relationships with random walks. Appendix E presents more details about the application of the proposed methodology to the ten directional corridor cases in Maryland and their various results.

## Incorporate Value of Travel Time Reliability into Project Evaluation Process

The local VTTR calculated using the travel-time data-driven methodology for estimating RR/VTTR was used to replace the current value in the baseline approach. The life-cycle BCA baseline approach that was documented as previously noted focused on congestion relief projects prioritized for the Baltimore Beltway. Sensitivity of the baseline prioritization results to changes in VTTR was investigated. The VTTR that made pairs of projects comparable or resulted in a re-prioritization of projects was identified.

## Brief SHA Management on Methods Used to Select and Defend Local Value of VTTR and Impacts of Application to Existing Decision Processes

The Maryland SHA Office of Planning and Preliminary Engineering leadership and stakeholders were briefed on project progress throughout the conduct of the research project. The research team was led by a member of SHA's Office of Planning and Preliminary Engineering. A presentation was prepared and made to upper management within SHA to gauge their reaction to the findings of this research. The presentation used during this meeting is included in Appendix C, and the results of the meeting are presented in Chapter 3.

CHAPTER 3

# Findings and Applications

## Overview of Process Used to Apply Value of Travel Time Reliability in Maryland

The high-level steps used to incorporate value of travel time reliability (VTTR) into the Maryland State Highway Administration (SHA) project evaluation and decision process were as follows:

### Step 1: Document Existing Project Selection Process

This step involved documenting the existing life-cycle benefit–cost analysis (BCA) process for which VTTR was being used in consideration of prioritizing congestion relief projects for implementation.

### Step 2: Define Trips/Corridors to Be Analyzed

This step involved selecting the routes and corridors connecting major O-D pairs for which a local value of reliability is desired. The selection should be done in conjunction with Step 3 to ensure that the required historical travel time data are available.

### Step 3: Acquire Data to Be Used for Analysis

The Maryland SHA has access to link-based historical travel time data based on vehicle probes (both INRIX and the National Performance Measures Research Data Set [NPMRDS]) for all highways and major arterials. Many DOTs across the country are already using vehicle probe–based travel time data.

### Step 4: Calculate Reliability Ratio/Value of Reliability

The research team used the travel-time data-driven methodology for estimating value of reliability developed as part of this project for calculating a local reliability ratio and value of reliability. The methodology used is explained in this chapter as well as in Part 2. The MATLAB code used to automate this process is included in Appendix B.

### Step 5: Incorporate RR into the Existing Short-Term Congestion Relief Project Selection Process

The local VTTR calculated using the travel-time data-driven methodology for estimating RR/VTTR was used to replace the current value in the baseline approach. The impact of replacing the RR currently used with a range of RRs was analyzed using projects selected in the past as a case study.

### Step 6: Incorporate RR into Long-Term Project Selection Process

This was accomplished using the Maryland Statewide Transportation Model (MSTM), a long-term travel demand model. The results are presented in this chapter, along with details of the process used.

### Step 7: Present to SHA Management

Maryland SHA stakeholders were briefed on project progress throughout the conduct of the research project. The research team was led by a member of SHA's Office of Planning and Preliminary Engineering. A presentation was prepared and made to upper management within SHA to gauge their reaction to the findings of this research. The presentation used during this meeting is included in Appendix C and the results of the meeting are presented at the end of this chapter.

## Description of Established Processes

The Maryland SHA project investment decision-making process is performed within an elaborate and complex framework that has been established over many years and involves the Maryland Department of Transportation (MDOT), local jurisdictions, and Metropolitan Planning Organizations (MPOs). Within the last 2–3 years, SHA, through the adoption of various measurement and reporting methodologies and tools, has been able to quantify current mobility conditions and trends on its highways including reliability performance measures. This provides a basis for examining how mobility conditions change with the evolving transportation environment, and to assess how the agency's actions can efficiently impact the users of the state's transportation system.

What follows in this section is a description of SHA's short-term congestion relief project prioritization and decision-making process, because it is this process in which SHA currently uses a value of travel time reliability. However, this short-term congestion relief process falls within a much larger decision-making framework and there are many other specific programming decision processes within this framework. For an overview of the larger Maryland Department of Transportation's investment decision process followed by SHA's high-level investment decision process, the reader is referred to Appendix A. Appendix A also includes some detail regarding other specific programming decision processes internal to SHA.

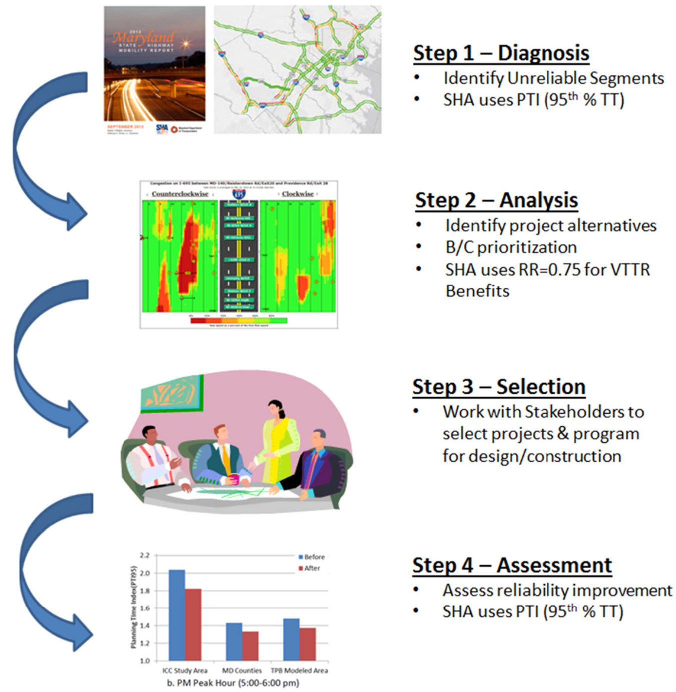



*Figure 3.1. Four-step process described for making investment decisions.*

## Description of Reliability in Congestion Relief Project Decision Making

From a reliability perspective, SHA has made significant inroads with incorporating reliability within short-term improvement studies to identify priority congestion relief projects. The four-step process that will be described (see Figure 3.1) for making investment decisions in these congestion relief projects is relatively new and incorporates an adopted reliability measure, value of time, and value of travel time reliability.

### Step 1: Diagnose Problems Including Highly Unreliable Segments/Corridors

In 2012, the Maryland SHA published its first of what has become an annual mobility report. This annual mobility report is an important document that helps SHA decision makers identify problematic state roadways where short-term congestion relief project investments should be made and reliability is a key component of the problem diagnosis. Significantly, reliability is becoming ingrained in SHA transportation policy as evidenced by this excerpt from the foreword of the 2013 Maryland State Highway Mobility Report as written by the SHA Administrator, Melinda B. Peters (Mahapatra et al., 2013):

> In addition to safety and congestion, transportation system reliability is another key factor to providing our customers with a good travel experience.

The congestion and reliability measures reported in the Maryland Mobility Report include travel time index (TTI) and planning time index (PTI). For PTI, 95th percentile reliable travel time is the selected measure that is calculated for SHA roadways and reported. These measures, TTI and PTI, were selected because they are easily computed from speed data and are relatively easy to communicate to a broad range of audiences. Speed data comes from a private company providing both real-time and historic traffic speed data collected from an estimated 100 million vehicles nationwide, including commercial vehicle fleets. Note that this is the same data source that is used in the travel-time data-driven methodology for estimating value of reliability developed as part of this project for calculating a local reliability ratio and value of reliability.

For the purposes of reporting PTI, the Maryland SHA has categorized the reliability-based value of PTI as follows:

- Reliable (PTI < 1.5)
- Moderately Unreliable (1.5 < PTI < 2.5)
- Highly Unreliable (PTI > 2.5)

This categorization was closely coordinated with the Washington and Baltimore Metropolitan Planning Organizations (MPOs) to ensure regional consistency in definition and reporting. Analysis and reporting of congestion and reliability measures is done by (1) entire state network, (2) major geographic regions, and (3) regionally significant corridors in the morning and evening peak hours. In addition, the Maryland SHA reports

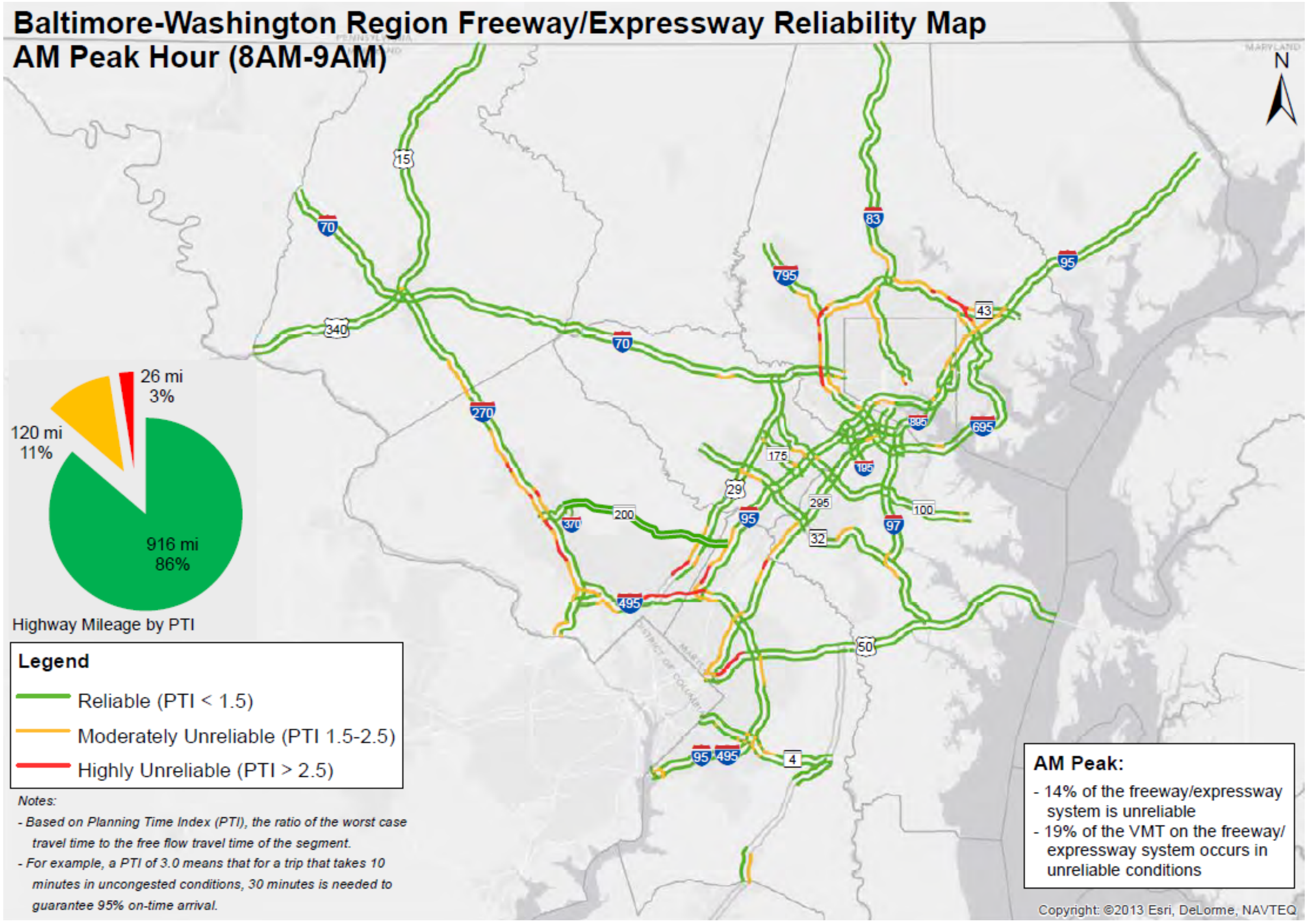



*Figure 3.2. SHA reports on reliability with a map focused on the Baltimore-Washington region.*

on the extent of reliability by reporting, for example, the percent of peak hour vehicle miles traveled (VMT) experiencing unreliable (PTI > 1.5) conditions. Figure 3.2 shows an example of how SHA reports on reliability with a map focused on the Baltimore-Washington region. In this region, 19% of the morning peak hour VMT experiences unreliable conditions.

The executive summary of both the 2012 and 2013 Maryland SHA Mobility Reports provides a summary of the top five most unreliable segments, as measured by PTI, in the morning and evening peak hours. In 2012, three of the top 10 most unreliable segments were on the Baltimore Beltway (I-695) as were three of the top 10 most congested segments. Based on these findings, the Baltimore Beltway was targeted for identifying and prioritizing congestion relief projects.

## Step 2: Identify Congestion Relief Alternatives and Prioritize Using Benefit–Cost Analysis

In this step, ongoing studies and projects already in the planning or design phase are identified for the targeted facility. In 2012, using the Baltimore Beltway (I-695) as an example, there were 10–15 projects in various stages of planning and design. In an effort to refine targeting of problem locations, input is gathered through field observations as well as input from regional planning personnel, Office of Highway Design, District personnel, Office of Construction, Office of Traffic and Safety, and the Office of Planning and Preliminary Engineering. A traffic simulation model (VISSIM) is used to support the project sequencing evaluation process for improvements to the roadway and to summarize the results of the analysis and provide prioritization for projects. Proposed projects are low-cost solutions that exclude any major roadway improvements, such as bridge widening or anything requiring major right-of-way acquisition. Proposed projects also take into account any projects that already are in the planning and design phases.

The I-695 study area included the southwest, northwest, and northeast segments as shown in Figure 3.3. Data used in the VISSIM analysis include morning and evening peak hour volumes (including ramp turning movements), the number

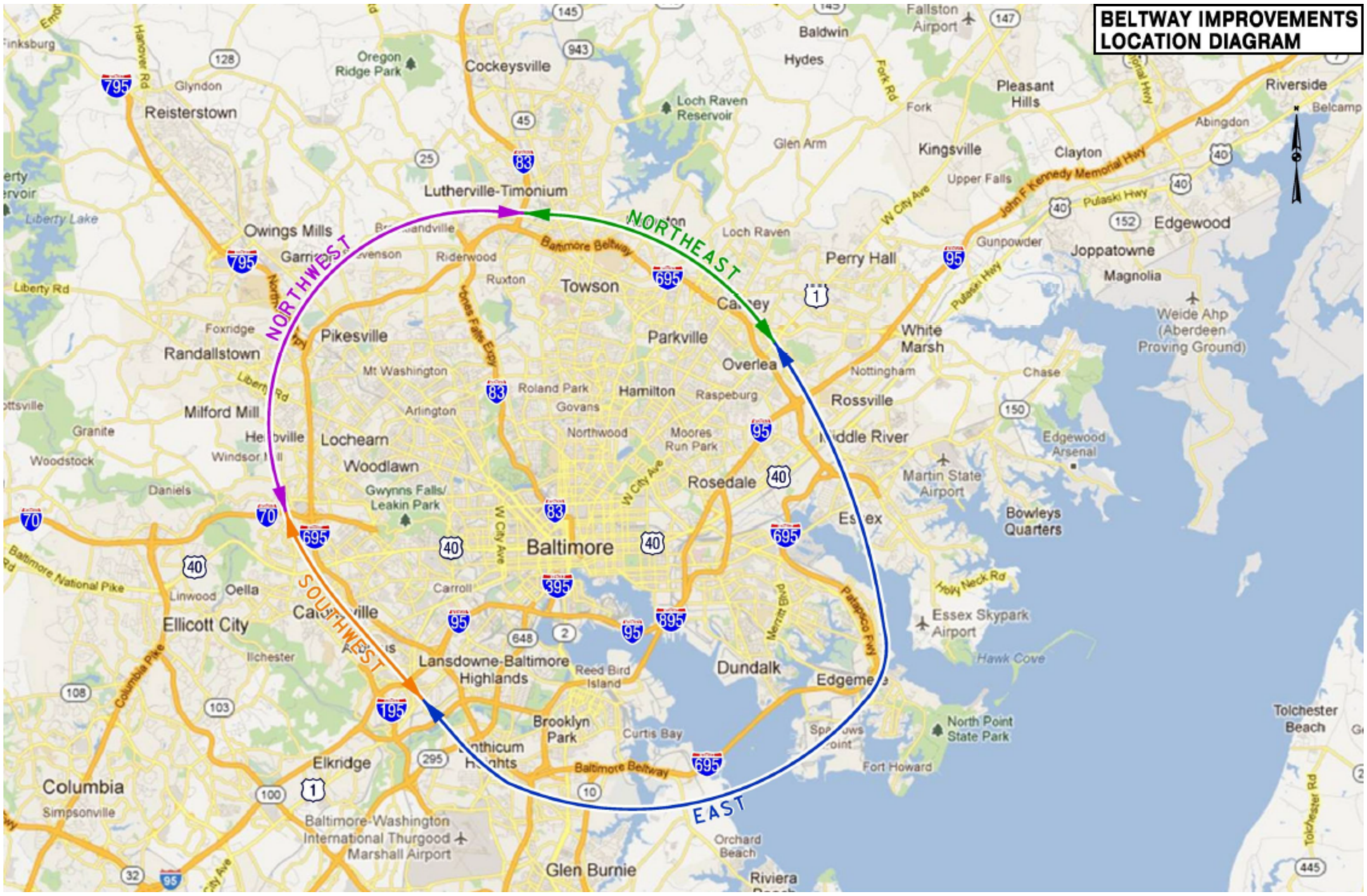



*Figure 3.3. The I-695 study area included the southwest, northwest, and northeast segments.*

of lanes that service the volume, percent trucks, and speeds based on vehicle probe data.

The VISSIM models are calibrated using the following criteria for each roadway segment along I-695 between interchanges as follows:

- Traffic volumes must be within 10% of the input volume.
- Auto speeds must be ±5 mph of the vehicle probe data speed.
- Auto travel times must be within 10% of the vehicle probe data travel time.

In order to calibrate the model, adjustments are made to driver behavior including lane change parameters, headways, and desired speed decisions. Models are run five times and data are averaged for the combined runs.

The majority of proposed improvements for I-695 provide auxiliary lanes between interchanges or the extension of acceleration lanes. Proposed improvements are run through a benefit–cost analysis. The speeds and travel times from VISSIM are compared between existing conditions and proposed improvements. In the I-695 study, the following assumptions were made in calculating benefits and costs, respectively:

- Benefits
  - Three hours of both the AM and PM peaks are considered
  - 250 working days per year
  - 20 year time horizon
  - 10% trucks
  - Auto congestion cost: $25.68/hour (2010)
  - Truck congestion cost: $66.08/hour (2010)
  - 1.2 average vehicle occupancy
  - Fuel cost estimated to be 10% of delay savings
  - 75% of delay savings as reliability savings (0.75 reliability ratio)
  - Safety benefits made using crash modification factors and year 2011 crash data
- Costs
  - Major quantities and unit pricing developed in accordance with 2010 SHA Highway Construction Cost Estimating Manual.

- Bridge widening that is necessary (outside of restriping alternatives) is by separate preceding contract unless otherwise noted.
- Retaining walls and concrete traffic barrier are assumed to stay within right-of-way within developed or known environmentally sensitive areas.
- An 800-foot length of grinding/resurfacing is assumed on each end of each alternative for maintenance of traffic (MOT) traffic shifts.
- Pavement section consists of 2-in. surface course, 15-in. base course, and 2 courses of 6-in. graded aggregate base.
- Ground mount signing and pavement markings estimated on cost-per-mile basis.
- Utility relocation estimated at 8% of neat construction cost.
- A 35% contingency and 15.3% overhead factor was applied to each alternative estimate.

SHA Business Plan objectives require at least a 5% reduction in delay due to the implementation of its congestion relief projects. Note that SHA's BCA process uses travel time savings (both savings in average and reliability) as part of the benefits calculation. Average travel time savings are calculated using traffic volume affected, average travel time improvement, and value of travel time (VOTT). Following recent trends of other transportation agency practices, particularly in Europe (where reliability benefits are accounted for as a percent of congestion reduction–related savings), SHA includes 75% of the congestion-related savings as reliability-related savings to project benefits. Note that the literature search performed on relevant national and international studies as well as the options-theoretic analysis on Maryland travel time data point to the fact that the current value (75%) is well within the range of viable values for the state of Maryland. Table 3.1 summarizes the latest basic parameters used in SHA's BCA process to estimate monetary value of travel time savings, travel time reliability savings, and fuel cost savings.

***Table 3.1. Parameters Used by SHA in Project Benefit Estimation (2012 Values)***

| Saving Type | Parameter | Unit | Categories | SHA Value |
|---|---|---|---|---|
| Travel time | VOTT | $/h | Passenger | 29.82 |
| | | | Truck driver | 20.21 |
| | | | Cargo | 45.40 |
| Travel time reliability | VTTR | $/h | Passenger | 22.36 |
| | | | Truck driver | 15.16 |
| | | | Cargo | 34.05 |
| Fuel cost | na | $/gal | Gasoline | 3.69 |
| | | | Diesel | 3.97 |

Note: na = not applicable.

In the baseline approach, the value of travel time for automobile passengers, truck drivers, and freight cargo are declared. These values are based on a series of studies that are primarily sponsored under SHA's CHART program to evaluate economic value of its incident management initiatives (Chang, 2011).

In the Chang 2011 study of CHART incident management program benefits, which reports on 2011 values, the passenger unit value of time is based on U.S. Census Bureau data (IndexMundi 2013; U.S. DOT 2013). A truck driver's value of time is based on information from the Bureau of Labor Statistics, the U.S. DOT, and FHWA's Highway Economic Requirements System (HERS) (FHWA, 2013). Similarly, the cargo value of time is based on a study by the Texas Transportation Institute, a study by Levinson and Smalkoski (2003), and a study by De Jong (2000).

## Step 3: Congestion Relief Project Selection

The output of the previous step provides a list of potential congestion relief projects along with their associated benefit–cost ratios. Table 3.2 below is an example of a subset of improvement projects that were developed for I-695 (note that a total of 16 projects were identified in the study area). Recommendations for project selection are made by the study analysis team. Final selection of projects is made by SHA leadership after meetings are held with various stakeholders, such as MDOT, the MPO, FHWA, and the district offices. Ultimately, projects selected are based on both quantitative and qualitative input as well as available budget. They are then programmed and moved forward into the design phase.

## Step 4: Post-Congestion Relief Project Implementation Assessment

After completion of the project, an impact assessment on congestion and reliability resulting from implementation is made. This is usually done four to six months after the project has opened in order to allow traffic to adjust to the new patterns.

Maryland uses congestion and reliability measures in project-specific impact assessment as well as in annual corridor assessments made as part of their Mobility report development and reporting process. An example of assessing a major capacity improvement project, Maryland Route 200, which is commonly known as the Intercounty Connector (ICC), was analyzed to determine its postconstruction impacts on congestion and reliability. Maryland Route 200 is a six-lane electronic toll facility connecting Interstates 270 and 95 in the Washington, D.C. metropolitan area. The analysis found that although the metropolitan area generally experienced better traffic conditions in

*Table 3.2. Subset of Improvement Projects That Were Developed for I-695*

| Location | Project Description | Total Savings ($, ×10³) | Construction Cost ($, ×10³) | O&M Cost ($, ×10³) | Total Cost ($, ×10³) | Benefit/Cost (%) |
|---|---|---|---|---|---|---|
| I-695 outer loop: US 40 (Baltimore National Pike) Interchange | Extend outer loop auxiliary lane prior to interchange to connect to deceleration lane to eastbound US 40. Widen I-695 outer loop to provide exclusive deceleration lane for westbound US 40. Total project length is 2,200 ft. | $32,894 | $5,000 | $500 | $5,500 | 598 |
| I-695 inner loop: MD 147 (Harford Road) Interchange | Remove eastbound I-695 to northbound (NB) MD 147 (Harford Road) ramp and replace with Signalized Spur off of eastbound I-695 to southbound (SB) MD 147 (Harford Road) ramp. | $9,117 | $2,368 | $237 | $2,605 | 350 |
| I-695 inner loop: MD 26 (Liberty Road) to I-795 (Northwest Expressway) | Provide 3 through lanes and 2 auxiliary lanes from eastbound MD 26 ramp to inner loop I-695 continuing to existing auxiliary lanes for northbound I-795 ramp. Project will require restriping and constructing new pavement and placement of a retaining wall. Total project length is 2,750 ft. | $30,702 | $9,900 | $990 | $10,890 | 282 |
| I-695 inner loop: MD 542 (Loch Raven Boulevard) to MD 41 (Perring Parkway) | Extend MD 542 (Loch Raven Boulevard) northbound to I-695 inner loop acceleration lane to bridge over East Joppa Road. Project includes milling and overlay for restriping and widening of I-695. Total project length is 3,000 ft. | $17,801 | $5,900 | $590 | $6,490 | 274 |
| I-695 outer loop: I-83 (Jones Falls Expressway) to Stevenson Road | Provide additional through lane from I-83 (Jones Falls Expressway) ramp to outer loop I-695 continuing to Stevenson Road off ramp. Project will involve mill and overlay to facilitate restriping existing pavement. Total project length is approximately 2 miles. | $15,177.26 | $5,400 | $540 | $5,940 | 256 |

2012 (after) than before (2010), the area in the vicinity of the ICC experienced greater magnitude improvements than did the region overall, by a margin of 3–4 percentage points, which is an indication of the ICC net effect (Pu et al., 2013). The analysis looked at the spatial extent of congestion, intensity of congestion, and reliability of travel both before and after the ICC in the morning and afternoon peak hours. Travel time reliability in the ICC study area, as measured by the 95th percentile travel time–based PTI, improved significantly after the ICC was constructed. As Figure 3.4 shows, in the AM peak hour, the ICC study area average PTI was 2.11 in 2010, and decreased to 1.85 in 2012, an 11% drop. In the PM peak hour, the PTI went from 2.04 in 2010 to 1.82 in 2012, an 11% drop.

Referring back to the Baltimore Beltway (I-695) example, the congestion relief projects selected to move forward to design have not yet been constructed. The Maryland SHA does, however, continue to monitor I-695 congestion and reliability performance overall as shown in the most recent mobility report (2013). The Baltimore Beltway is one of many regionally significant corridors that is measured annually in terms of congestion and reliability performance (see Figure 3.5).

## Proposed Travel-Time Data-Driven Methodology for Estimating Value of Reliability/Reliability Ratio

As described in the previous section, SHA is using planning time index (PTI) to measure travel time reliability on highway facilities. The Maryland SHA has also adopted a 0.75 reliability ratio (RR) to measure the economic benefits of improvements in travel time reliability when conducting benefit–cost analysis of congestion relief projects. Conventionally, RR is defined as the ratio of value of travel time reliability (VTTR) and value of travel time (VOTT). This value was adopted by the Maryland SHA based on a comprehensive literature search of existing national and international resources as well as existing federal recommendations for a

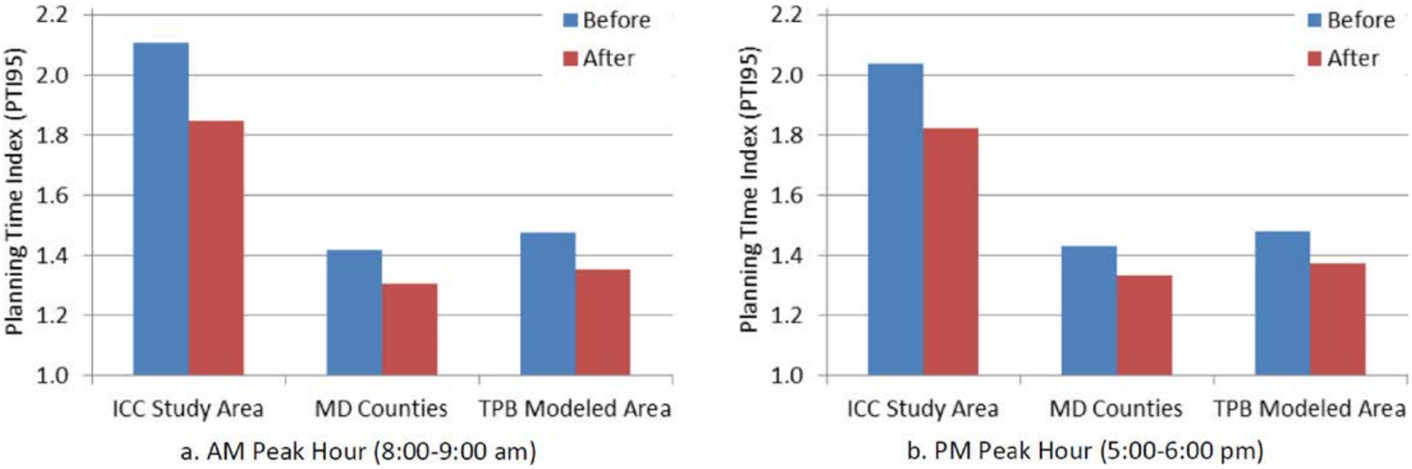



*Figure 3.4. ICC study area average PTI for AM and PM peak hours. (Before = 2010; after = 2012.)*

RR value. One of the objectives of this research was to develop a methodology to defend this number or provide a basis for changing it based on local data.

A travel-time data-driven methodology is proposed for estimating a reliability ratio (RR) and ultimately a value of travel time reliability (VTTR). The methodology has been implemented in MATLAB to automate the process (the MATLAB code is provided in Appendix B). An entire year's worth of archived probe-based travel time data was used to estimate the local RR and VTTR values on five different corridors in Maryland.

What follows is an overview of the proposed methodology to value travel time reliability which is based on Real Options theory. A detailed in-depth treatment of the methodology's development, its assumptions, example application, and calculations, as well as how it differs from and builds on the previous application of Real Options theory, is provided in Part 2.

The proposed method is based on an analogy of a travel time insurance policy. The method requires historical travel time data over an extended period of time as input and performs the necessary analysis to identify the nature and size of travel time variations that are experienced by travelers.

Once the stochastic nature of variations in travel time is identified, it can be used to build a projected probability density function of travel time realizations over an extended period given prevailing infrastructure and traffic conditions.

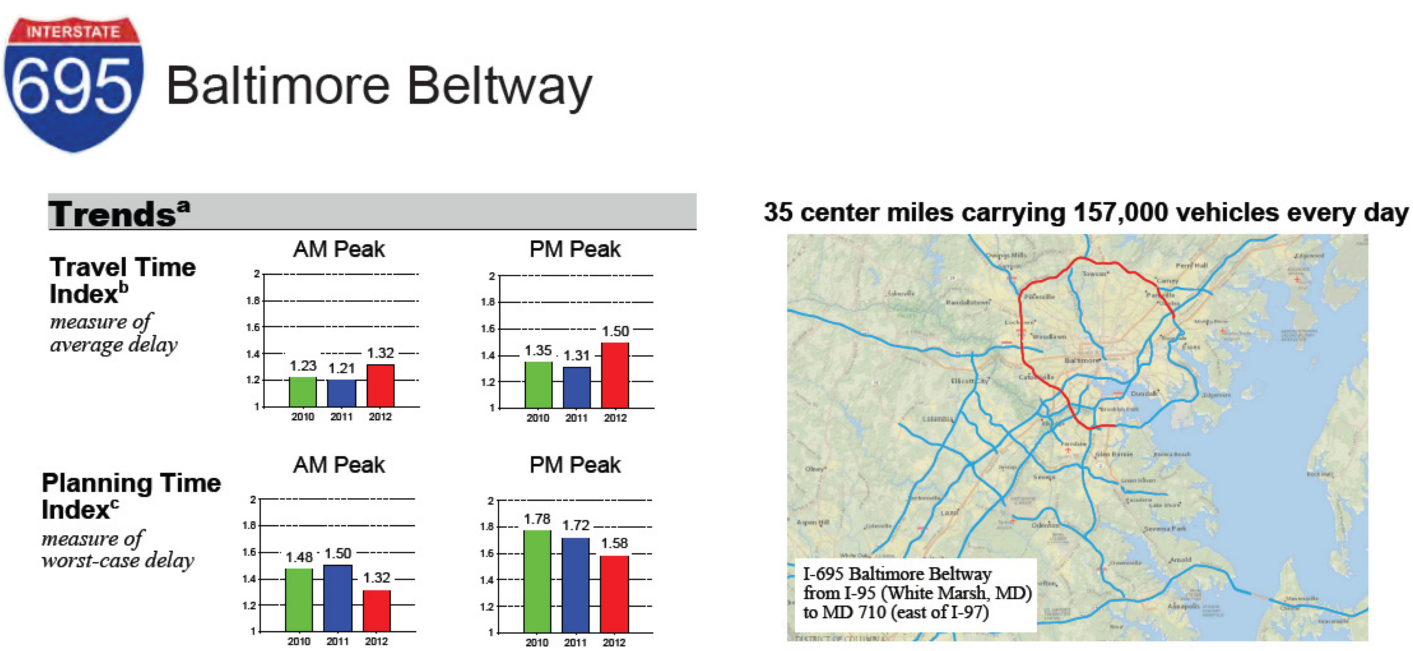



*Figure 3.5. The Baltimore Beltway is measured annually in terms of congestion and reliability performance.*

Travelers are assumed to incur penalties associated with arriving earlier or later than their planned arrival times at their destination. In the proposed method, these penalties are defined as a fixed portion of the amount of time by which the traveler is early or late relative to their planned arrival time. The estimated penalties are used to evaluate the certainty-equivalent insurance policy that will offer the traveler equal coverage against expected future penalties.

Note that in characterizing the valuation method the following questions need to be answered:

1. How can travel time evolutions over time be modeled?
2. How can a penalty/reward (payoff) of early/late arrivals at the destination be determined?
3. What is the guaranteed level of travel time?
4. What is the duration of time for which the travel time insurance policy is issued?
5. How do the future payoffs get valued at the outset of the trip?

Figure 3.6 illustrates the above-mentioned components of an options-theoretic valuation method. Note that this is a generic graphic. The methodology is fully described by specifying each component of the method in Part 2. In essence, the following set of responses to the corresponding set of questions above provides a high-level description of the proposed methodology:

1. Travel time series can be characterized as geometric Brownian motion (GBM) with drift stochastic process; hence, given the process parameters, future travel time probability distributions can be specified.
2. Penalty is simply defined as an asymmetric bilinear function of the amount of time by which the traveler is late or early at the destination.
3. Expected travel time is taken as the guaranteed travel time level.
4. Travel time insurance policy is issued for the longest trip time possible under recurrent congestion scenarios (95th percentile travel time is used for this purpose).
5. A certainty-equivalent payoff valuation strategy is adopted. This payoff valuation method takes advantage of the GBM assumption for the travel time process to greatly simplify the insurance valuation process.

The results of applying the methodology indicate that SHA's use of the current RR of 0.75 is conservative for commute trips. According to U.S. Census Bureau statistics, average commute trips in Maryland during the 5-year period (2006–2010) have been approximately 31 minutes long (IndexMundi 2013; U.S. DOT 2013). However, the corresponding RR value (0.87) is believed to be at the upper range of values for travel time reliability. Further analysis was conducted to justify any decision to increase the current value of travel time reliability.

Maryland Statewide Transportation Model (MSTM) long-term demand and travel time estimates are used in aggregating the results for all origin–destination (O-D) pairs in the state. Based on MSTM, for all current trip purposes, an average reliability ratio value of 0.52 is obtained. This value is expected to increase to 0.55 over the next 15 years until 2030. Similarly, the current average reliability ratio for commute trips in Maryland is estimated to be 0.68 and would remain relatively unchanged until 2030. However, it should be noted that in comparison with U.S. Census Bureau estimates, MSTM travel times are on

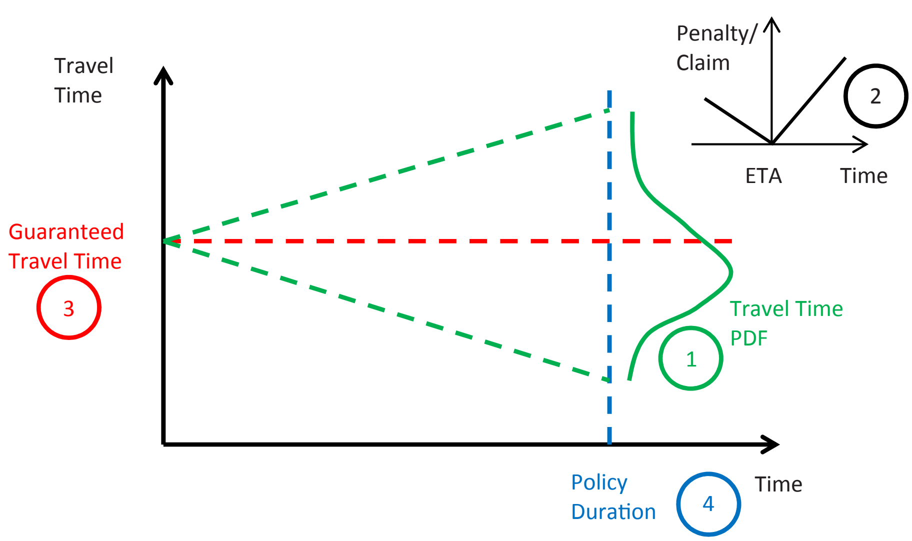



***Figure 3.6. Various components of a travel time insurance pricing method.***

average about 6 minutes smaller. Note that due to bias in self-reporting, Census Bureau estimates tend to be an overestimate. At the same time, it may be argued that MSTM travel times are underestimates caused by spatial aggregations in zone definitions as well as the use of long-term performance functions.

In summary, it can be concluded that, during peak hours in congested urban areas, the average reliability ratio ranges between 0.68 and 0.87 derived from MSTM and Census Bureau travel times, respectively. In nonurban areas and at off-peak hours, the average reliability ratio can be taken as 0.52. Therefore, it seems the current value (0.75) is reasonable when the reliability of commute travel times during peak hours in congested urban areas is concerned.

## Incorporating Results into Short-Term Prioritization and Project Selection

In order to incorporate the findings of this study into the short-term prioritization and project selection process at the Maryland SHA, improvement projects on I-695 (Baltimore Beltway) were selected as a case study. All proposed congestion relief projects are low-cost solutions that exclude any major roadway improvements, such as bridge widening and major right-of-way acquisition. Projects were analyzed using VISSIM. The resultant travel time and reliability savings as well as corresponding project costs are used to rank each project.

This study includes I-695 between MD 43 in White Marsh and I-95 in Arbutus and will be expanded in the future to include the remainder of the Beltway, which includes the entire east side. The I-695 study area includes the entire Baltimore Beltway in Baltimore County, Anne Arundel County, and Baltimore City. For analysis purposes, I-695 was divided into the following segments as shown in Figures 3.3 and 3.7:

- Northeast—from I-83 (Harrisburg Expressway) to MD 43 (White Marsh Boulevard)
- Northwest—from I-70 to I-83 (Harrisburg Expressway)
- Southwest—from I-95 (Arbutus) to I-70

Existing AM and PM peak hour volumes were developed for the study area using information provided by the Highway Information Services Division (HISD) website as well as the O-D study conducted for the I-695 inner loop weave from

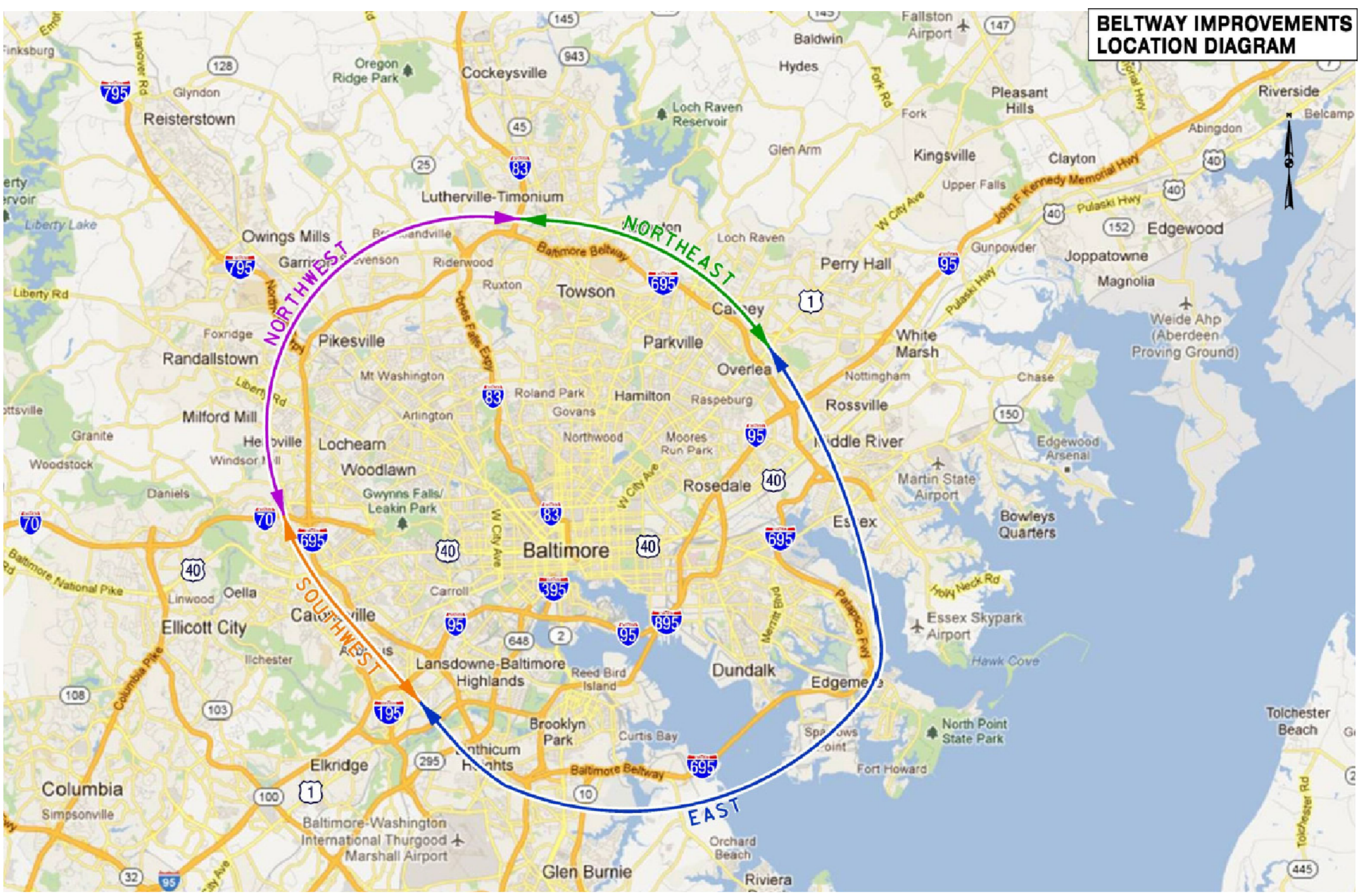



*Figure 3.7. Baltimore Beltway (I-695) study area.*

*Table 3.3. Proposed Improvement Projects in the Southwest Quadrant of the Baltimore Beltway*

| Project Code | Location | Improvement Description |
|---|---|---|
| SW1 | I-695 outer loop: MD 144 (Edmonson Avenue) on ramp continuing to MD 372 (Wilkens Avenue) | Provide additional through lane from on ramp at Edmonson Avenue to end of acceleration lane from Edmonson Avenue. Project includes widening and restriping of I-695 outer loop and removal and placement of retaining wall. Total project length is 2,500 ft. |
| SW2 | I-695 inner loop: US 40 (Baltimore National Pike) Interchange | Extend inner loop auxiliary lane prior to interchange to connect to deceleration lane to westbound US 40. Widen I-695 inner loop to provide exclusive deceleration lane for eastbound US 40. Includes construction of retaining wall. Total project length is 2,200 ft. |
| SW3 | I-695 outer loop: US 40 (Baltimore National Pike) Interchange | Extend outer loop auxiliary lane prior to interchange to connect to deceleration lane to eastbound US 40. Widen I-695 outer loop to provide exclusive deceleration lane for westbound US 40. Total project length is 2,200 ft. |
| SW4 | I-695 inner loop: I-70/MD 122 (Security Boulevard) to Windsor Mill Road | Extend I-70 WB to I-695 NB acceleration lane by 500 ft. Extend MD 122 to I-695 NB acceleration lane by 1,250 ft. Project will require restriping of I-695, widening to accommodate acceleration lane and construction of a retaining wall. |

northbound MD 41 (Perring Parkway) to MD 43 eastbound. The volumes include the turning movements at ramp termini. The truck percentage throughout the study area varies between 5% and 12% for both peak hours.

The models were created using VISSIM 5.3-09 for both the AM and PM peak hours. In order to minimize the effort in the calibration process, signalized intersections were excluded from the models. Calibration criteria for each roadway segment along I-695 between interchanges are as follows:

- Traffic Volumes must be within 10% of the input volume.
- Auto Speeds ±5 MPH of the INRIX speed.
- Auto Travel Times must be within 10% of the INRIX travel time.

All models were calibrated within the targeted ranges. In order to calibrate the model, adjustments were made to driver behavior including lane change parameters, headways, and desired speed decisions. Most modifications were made at heavy merge and weave areas. Seeding times varied between 15 minutes and 1 hour depending on the congestion level of the roadway. Models were run five times and data was averaged for the combined runs.

## Improvement Projects

Several improvements were proposed for the I-695 corridor. These improvements do not include any bridge widening other than those bridge widening projects that are already funded for construction. Most improvements provide auxiliary lanes between interchanges or the extension of acceleration lanes. Tables 3.3 through 3.5 provide a complete list of proposed improvements in each quadrant of the Beltway.

The resultant speeds and travel times obtained from VISSIM models were compared between the existing conditions and proposed improvements. Benefit-to-cost comparison

*Table 3.4. Proposed Improvement Projects in the Northwest Quadrant of the Baltimore Beltway*

| Project Code | Location | Improvement Description |
|---|---|---|
| NW1 | I-695 inner loop: MD 26 (Liberty Road) to I-795 (Northwest Expressway) | Provide 3 through lanes and 2 auxiliary lanes from eastbound MD 26 ramp to inner loop I-695 continuing to existing auxiliary lanes for northbound I-795 ramp. Project will require restriping and constructing new pavement and placement of a retaining wall. Total project length is 2,750 ft. |
| NW2 | I-695 outer loop: I-795 (Northwest Expressway) to MD 26 (Liberty Road) | Provide auxiliary lane from I-795 (Northwest Expressway) Ramp to outer loop I-695 continuing to MD 26 (Liberty Road) off ramp. Project will include restriping, widening, construction of retaining wall, and placement of W-beam traffic barrier. Total project length is 3,800 ft. |
| NW3 | I-695 outer loop: I-83 (Jones Falls Expressway) to Stevenson Road | Provide additional through lane from I-83 (Jones Falls Expressway) ramp to outer loop I-695 continuing to Stevenson Road off ramp. Project will involve mill and overlay to facilitate restriping existing pavement. Total project length is approximately 2 miles. |
| NW4 | I-695 inner loop: Stevenson Road to I-83 (Jones Falls Expressway) | Provide additional through lane from Stevenson Road to auxiliary lane for southbound I-83 (Jones Falls Expressway). Project will involve mill and overlay to facilitate the restriping for the additional lane. Total project length is approximately 7,900 ft. |

*Table 3.5. Proposed Improvement Projects in the Northeast Quadrant of the Baltimore Beltway*

| Project Code | Location | Improvement Description |
|---|---|---|
| NE1 | I-695 inner loop: MD 139 (Charles Street) to MD 146 (Dulaney Valley Road) | Provide auxiliary lane from West Road exit to northbound MD 146 (Dulaney Valley Road) exit. Project includes widening for 500-ft deceleration lane at West Road exit. Project will also require milling and overlay for restriping and construction of retaining wall. Total project length is 5,200 ft. |
| NE2 | I-695 inner loop: MD 146 (Dulaney Valley Road) to Providence Road | Provide auxiliary lane from MD 146 (Dulaney Valley Road) northbound off ramp to Providence Road underpass. Includes mill and overlay for restriping, I-695 inner loop widening, and placement of W-beam traffic barrier. Total project length is 6,300 ft. |
| NE3 | I-695 outer loop: MD 542 (Loch Raven Boulevard) to Providence Road | Provide additional through lane from on ramp MD 542 (Loch Raven Boulevard) to outer loop I-695 continuing to Providence Road off ramp. Includes mill and overlay for restriping, I-695 outer loop widening, and placement of noise barrier and W-beam traffic barrier. Total project length is 3,700 ft. |
| NE4 | I-695 outer loop: Providence Road to MD 146 (Dulaney Valley Road) | Provide auxiliary lane from Providence Road to Dulaney Valley Road off ramp. Includes mill and overlay for restriping, I-695 outer loop widening, and placement of noise barrier and W-beam traffic barrier. Total project length is 5,200 ft. |
| NE5 | I-695 inner loop: MD 542 (Loch Raven Boulevard) to MD 41 (Perring Parkway) | Extend MD 542 (Loch Raven Boulevard) northbound to I-695 inner loop acceleration lane to bridge over East Joppa Road. Project includes milling and overlay for restriping and widening of I-695. Total project length is 3,000 ft. |
| NE6 | I-695 inner loop: MD 41 (Perring Parkway) to MD 147 (Harford Road) | Provide auxiliary lane from MD 41 (Perring Parkway) northbound ramp to inner loop I-695 continuing to and terminating at off ramp at MD 147 (Harford Road) southbound. Total project length is 3,900 ft. |
| NE7 | I-695 outer loop: MD 147 (Harford Road) to MD 41 (Perring Parkway) | Provide auxiliary lane from southbound MD 147 (Harford Road) ramp to outer loop of I-695 continuing to off ramp for northbound MD 41 (Perring Parkway). Total project length is 3,900 ft. |
| NE8 | I-695 inner loop: MD 147 (Harford Road) Interchange | Remove eastbound I-695 to northbound MD 147 (Harford Road) ramp and replace with signalized spur off of eastbound I-695 to southbound MD 147 (Harford Road) ramp. |

was developed, and the results are shown in Table 3.6. The following assumptions were made in the development of user savings under the current process:

- Three hours of AM peak and three hours of PM peak considered
- 250 working days per year
- 20 years
- Assume 10% trucks
- Auto congestion cost: $25.68/hour
- Truck congestion cost/hour: $66.08/hour
- Assume 1.2 average vehicle occupancy
- Fuel cost savings is assumed to be 10% of delay savings
- Assume 75% of delay savings as reliability savings (non-recurrent savings)
- Safety benefit using crash modification factors and year 2011 crash data

Major quantity estimates have been developed for each primary and long-term auxiliary lane alternatives using the following nine assumptions:

1. Measurements have been taken from base mapping, when available. When such base mapping was not available, measurements and cut heights were estimated using Google Map. Significant embankment and retaining wall heights within fill conditions were visually estimated by field visits as necessary.
2. Major quantities and unit pricing were developed in accordance with the 2010 SHA Highway Construction Cost Estimating Manual as practical. Major quantities percentages were supplied for Categories 1, 3, and 7 for the appropriate pavement type (restriping or pavement widening).
3. Bridge widening that is necessary (outside of restriping alternatives) is by separate preceding contract unless otherwise noted.
4. Estimates are for construction costs only. Retaining walls and concrete traffic barrier are assumed as noted to stay within right-of-way within developed or known environmentally sensitive areas, as well as to avoid impacts to noise walls. Right-of-way costs for environmental mitigation may be significant and should be estimated separately during preliminary design.
5. Except where otherwise noted, an 800-foot length of grinding/resurfacing is assumed on each end of each alternative for MOT traffic shifts. In remaining instances, MOT shifts on entire lengths of approach curves were assumed as noted.

*Table 3.6. Improvement Projects Benefit–Cost Analysis Under Current Value of Reliability (RR = 0.75)*

| Project Code | Vehicle Minutes Saved | | Peak Period Savings (h, ×10³) | Auto Cost Savings ($, ×10³) | Freight Cost Savings ($, ×10³) | Delay Cost Savings ($, ×10³) | Fuel Cost Savings ($, ×10³) | Reliability Savings ($, ×10³) | Safety Savings ($, ×10³) | Total Savings ($, ×10³) | Construction Cost ($, ×10³) | O&M Cost ($, ×10³) | Total Cost ($, ×10³) | Benefit/Cost (%) | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SW1 | AM PEAK | 1,542 | 386 | 10,692 | 2,547 | 13,239 | 1,324 | 9,929 | 989 | 27,164 | 16,500 | 1,650 | 18,150 | 150 | 10 |
| | PM PEAK | 106 | 27 | 735 | 175 | 910 | 91 | 683 | | | | | | | |
| SW2 | AM PEAK | 663 | 166 | 4,597 | 1,095 | 5,692 | 569 | 4,269 | 3,408 | 14,558 | 10,900 | 1,090 | 11,990 | 121 | 12 |
| | PM PEAK | 39 | 10 | 270 | 64 | 335 | 33 | 251 | | | | | | | |
| SW3 | AM PEAK | 352 | 88 | 2,441 | 582 | 3,022 | 302 | 2,267 | 26,398 | 32,894 | 5,000 | 500 | 5,500 | 598 | 1 |
| | PM PEAK | 57 | 14 | 395 | 94 | 489 | 49 | 367 | | | | | | | |
| SW4 | AM PEAK | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4,397 | 26,665 | 13,300 | 1,330 | 14,630 | 182 | 6 |
| | PM PEAK | 1,402 | 351 | 9,721 | 2,316 | 12,037 | 1,204 | 9,028 | | | | | | | |
| NW1 | AM PEAK | 62 | 16 | 430 | 102 | 532 | 53 | 399 | 26,779 | 30,702 | 9,900 | 990 | 10,890 | 282 | 3 |
| | PM PEAK | 185 | 46 | 1,283 | 306 | 1,588 | 159 | 1,191 | | | | | | | |
| NW2 | AM PEAK | 457 | 114 | 3,169 | 755 | 3,924 | 392 | 2,943 | 2,252 | 10,416 | 11,300 | 1,130 | 12,430 | 84 | 15 |
| | PM PEAK | 57 | 14 | 395 | 94 | 489 | 49 | 367 | | | | | | | |
| NW3 | AM PEAK | 447 | 112 | 3,099 | 738 | 3,838 | 384 | 2,878 | 1,597 | 15,177 | 5,400 | 540 | 5,940 | 256 | 5 |
| | PM PEAK | 408 | 102 | 2,829 | 674 | 3,503 | 350 | 2,627 | | | | | | | |
| NW4 | AM PEAK | 106 | 27 | 735 | 175 | 910 | 91 | 683 | 4,540 | 6,922 | 5,700 | 570 | 6,270 | 110 | 14 |
| | PM PEAK | 44 | 11 | 305 | 73 | 378 | 38 | 283 | | | | | | | |
| NE1 | AM PEAK | 114 | 29 | 790 | 188 | 979 | 98 | 734 | 1,573 | 27,717 | 16,100 | 1,610 | 17,710 | 157 | 8 |
| | PM PEAK | 1,532 | 383 | 10,622 | 2,531 | 13,153 | 1,315 | 9,865 | | | | | | | |
| NE2 | AM PEAK | 4 | 1 | 28 | 7 | 34 | 3 | 26 | 989 | 4,403 | 8,000 | 800 | 8,800 | 50 | 16 |
| | PM PEAK | 211 | 53 | 1,463 | 349 | 1,812 | 181 | 1,359 | | | | | | | |
| NE3 | AM PEAK | 494 | 124 | 3,425 | 816 | 4,241 | 424 | 3,181 | 798 | 8,644 | 6,300 | 630 | 6,930 | 125 | 11 |
| | PM PEAK | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | | | |
| NE4 | AM PEAK | 486 | 122 | 3,370 | 803 | 4,173 | 417 | 3,129 | 858 | 14,200 | 7,500 | 750 | 8,250 | 172 | 7 |
| | PM PEAK | 354 | 89 | 2,454 | 585 | 3,039 | 304 | 2,279 | | | | | | | |
| NE5 | AM PEAK | 6 | 2 | 42 | 10 | 52 | 5 | 39 | 1,347 | 17,801 | 5,900 | 590 | 6,490 | 274 | 4 |
| | PM PEAK | 1,030 | 258 | 7,142 | 1,702 | 8,843 | 884 | 6,632 | | | | | | | |
| NE6 | AM PEAK | 107 | 11 | 309 | 74 | 383 | 38 | 287 | 1,049 | 14,860 | 8,800 | 880 | 9,680 | 154 | 9 |
| | PM PEAK | 1,980 | 206 | 5,720 | 1,363 | 7,083 | 708 | 5,312 | | | | | | | |
| NE7 | AM PEAK | 1,225 | 128 | 3,539 | 843 | 4,382 | 438 | 3,287 | 2,228 | 10,937 | 8,800 | 880 | 9,680 | 113 | 13 |
| | PM PEAK | 91 | 9 | 263 | 63 | 326 | 33 | 244 | | | | | | | |
| NE8 | AM PEAK | 155 | 16 | 448 | 107 | 554 | 55 | 416 | 83 | 9,117 | 2,368 | 237 | 2,605 | 350 | 2 |
| | PM PEAK | 1,210 | 126 | 3,496 | 833 | 4,329 | 433 | 3,246 | | | | | | | |

6. The assumed pavement section consists of 2-in. surface course, 15 in. of base course, and two courses of 6-in. graded aggregate base.
7. Ground mount signing and pavement markings were estimated by cost-per-mile estimates. With the exception of the restriping alternatives and replacement of sign structures, roadway lighting and intelligent transportation systems (ITS) were estimated separately as noted within each estimate.
8. Utility relocation costs were estimated at 8% of the neat construction cost.
9. A 35% contingency and overhead factor of 15.3% was applied to each alternative estimate.

Table 3.6 presents a detailed description of various cost and savings estimates associated with each improvement. Benefit–cost analysis and resulting priority rankings for each improvement project under the existing reliability ratio scenario (0.75) are also reported.

Table 3.7 summarizes the sensitivity of project rankings to the reliability ratio scenario when RR values are varied between zero and 1.2 at 0.05 increments. In other words, Table 3.7 indicates how increasing relative value of travel time reliability savings as an index of travel time (delay) savings has contributed to the ranking of different projects. Figure 3.8 exhibits the same sensitivity analysis findings as in Table 3.7. Note that Figure 3.8 facilitates the visual inspection of changes in the rankings of a given project when RR values are varied.

Figure 3.8 illustrates the changes in project rankings when RR is varied from 0 to 1.2. It should be noted that in this analysis, the top ranked project (SW3) has a high benefit–cost ratio, approximately 600%. As a result, SW3 is not challenged by any other project as the RR is varied. Among the top five projects, the project ranked second goes progressively down in ranking when the RR increases to 0.35, 0.85, and 1.05. Projects ranked six through nine are stable throughout this range. The project originally (when RR = 0) ranked 10 also dropped in the rankings as the RR is progressively increased to 0.1, 0.4, and 0.75. From this graph it can be seen that the majority of changes happen in the 0.35–0.45 range. At higher RR values (larger than 0.7) the switch between projects is few and far between.

Figure 3.9 demonstrates the effect of budget constraints on project selection under different RR scenarios. It should be noted that at budgets less than $31,425,000, the top five projects (SW3, NW1, NE8, NE5, and NW3) compete for funding. SW3, with a total cost of $5,500,000, is always the first choice. When RR varies between 0.65 and 0.90, NE8, with a total cost of $2,605,000, is always the second choice. In this range, when RR is less than 0.85, NW1, with a total price tag of $10,890,000, is the third choice. However, at RR levels larger than 0.85, NE5, with a smaller total cost of $6,490,000, will be the third choice. Throughout this range, NW3 is the fifth choice for funding at a total price tag of $5,940,000. So, it can be concluded that at low budget levels the choice of RR can be crucial in prioritizing and selecting projects as is evident in the switch between more expensive NW1 and cheaper NE5. In this case increasing RR to 0.85 has caused NE5 (which is relatively more advantageous in terms of reliability) to obtain higher priority over NW1.

Delving a bit deeper into the details of projects NW1 and NE5 shows that quantitative analysis of improvement costs and savings depends on various project-specific factors including existing and projected volumes, safety-related statistics, adopted mitigation factors, and the number and configuration of existing lanes, among other things. Therefore, among low-budget-type improvements considered on I-695 (which are typically of a similar nature), rankings are mainly influenced by relative improvements in delay and travel time reliability, as well as traffic demand levels and presence and frequency of severe incidents at each location.

Note that the analysis results obtained from these short-term improvement projects are based on aggregate travel time savings. Therefore, to estimate the VTTR benefits, a constant factor of 0.75 was applied to the reported VOTT savings. The reader should note that this is an approximation and effectively reflects the implicit assumption that all O-D pairs affected by the proposed improvements have the same travel times and volumes in before/after scenarios. The research team acknowledges this significant assumption; however, in the absence of detailed O-D information for short-term improvement project analysis (and perhaps in similar practical decision-making scenarios), this exemplifies the versatility of the proposed reliability valuation method.

Also, note that, in this analysis, each improvement is evaluated independent of the other proposed improvements. In practice, the interactions between nearby improvements should be taken into account.

In the next section the results of incorporating the proposed VTTR estimation method into long-term prioritization and project selection are presented. In this case, disaggregate O-D information is used to estimate VOTT and VTTR savings. Also, in this application interactions between different projects under the framework of a long-term regional transportation planning model are taken into account.

## Incorporating Results into Long-Term Prioritization and Project Selection

In order to incorporate the findings of this study into the long-term prioritization and project selection process at the Maryland SHA, a postprocessing module was developed for the Maryland Statewide Transportation Model (MSTM). These efforts illustrated that the travel time reliability valuation process and its corresponding savings estimation can be easily integrated into any regional travel demand model. However, note that these results should only be regarded as a proof of concept.

*Table 3.7. Sensitivity Analysis on Improvement Project Rankings with Various Reliability Ratios*

| Project Code | 0 | 0.05 | 0.1 | 0.15 | 0.2 | 0.25 | 0.3 | 0.35 | 0.4 | 0.45 | 0.5 | 0.55 | 0.6 | 0.65 | 0.7 | 0.75 | 0.8 | 0.85 | 0.9 | 0.95 | 1 | 1.05 | 1.1 | 1.15 | 1.2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SW1 | 11 | 11 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| SW2 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 11 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| SW3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| SW4 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| NW1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 |
| NW2 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| NW3 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 |
| NW4 | 10 | 10 | 11 | 11 | 11 | 11 | 11 | 11 | 13 | 13 | 13 | 13 | 13 | 13 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 |
| NE1 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| NE2 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 |
| NE3 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 12 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| NE4 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| NE5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| NE6 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| NE7 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| NE8 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

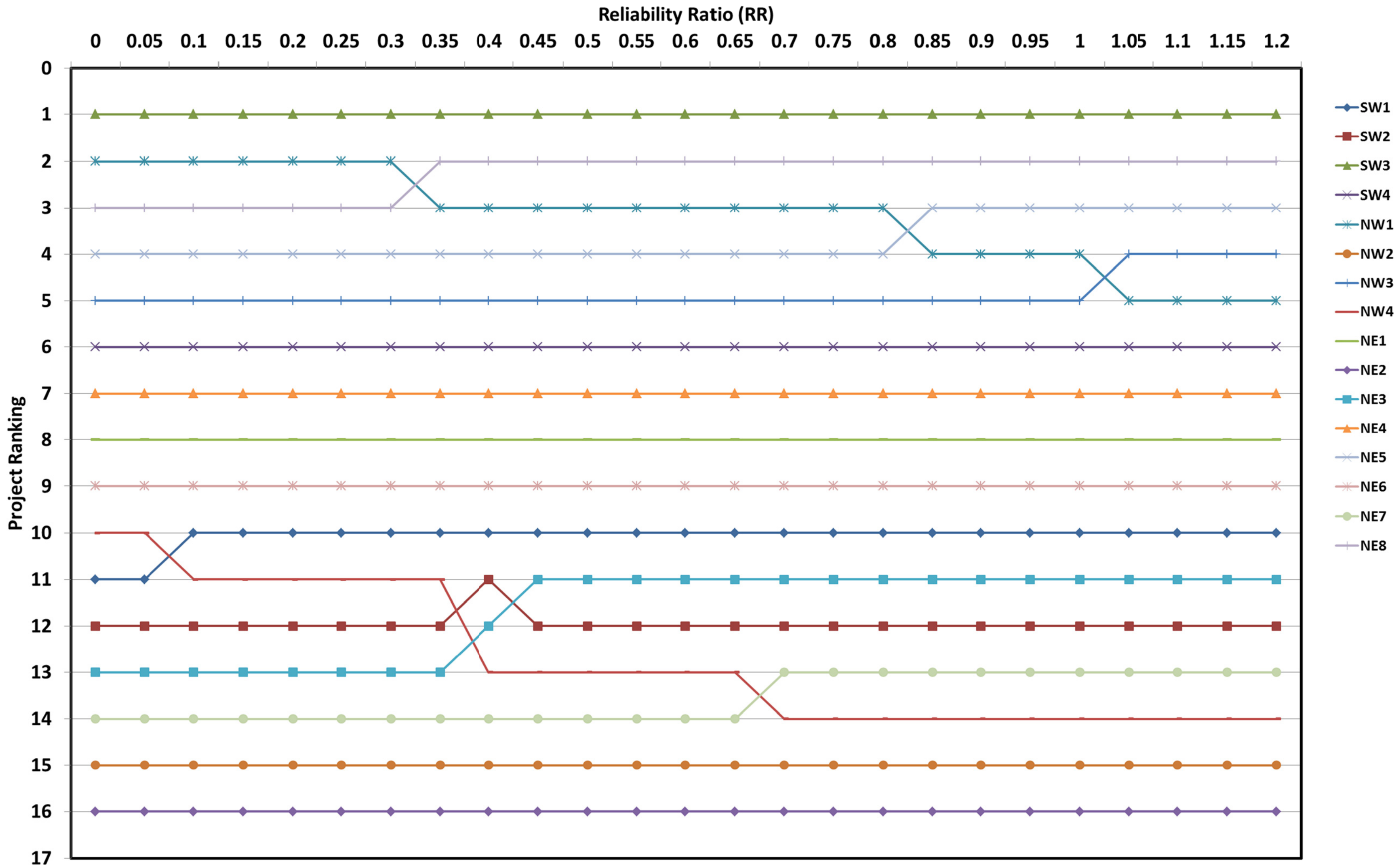



*Figure 3.8. Improvement project rankings under various reliability ratios.*

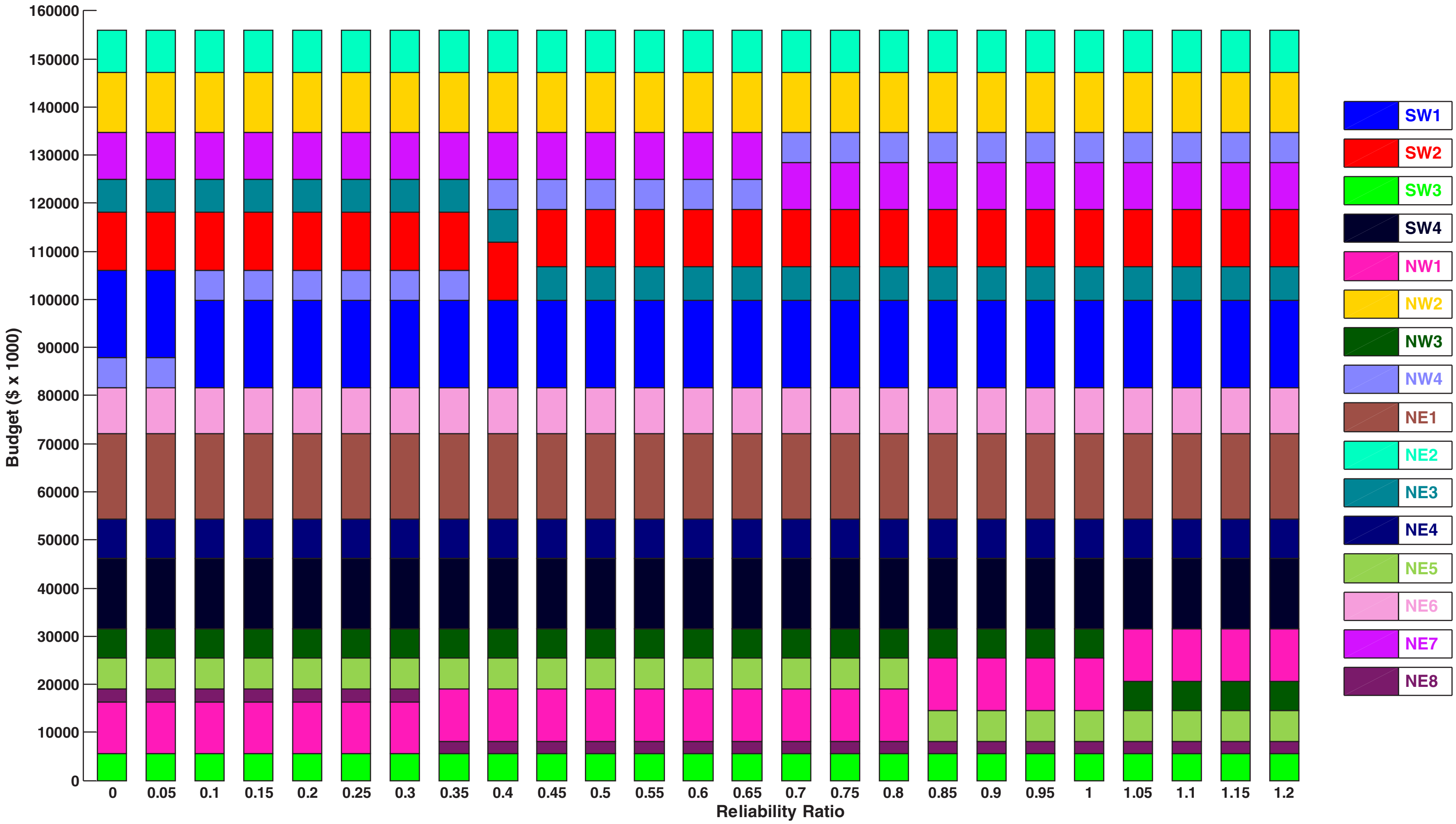



***Figure 3.9. Impacts of different reliability ratio and budget levels on selected improvement projects.***

Future research directions should include integration of a calibrated reliability ratio model into travel behavior models.

One of the integral findings of SHRP 2 L35B is the data-driven empirical model to compute reliability ratio (RR). Previously, RR has been defined as the ratio of VTTR to VOTT; however for the purposes of this long-term prioritization analysis, it can also be defined as the ratio of the system benefits from travel reliability enhancements to the system benefits from travel time savings. This ratio, in theory, should differ based on transportation facility type, level of congestion, vehicle fleet composition, time of day, trip purpose, etc. The proposed empirical formula for RR was used to compute travel time savings and travel time reliability savings for four scenarios:

1. Base year—build;
2. Base year—no build;
3. Future year—build; and
4. Future year—no build.

The base and future years are 2010 and 2030 respectively. The base case—no build scenario represents the network conditions prior to construction of the Intercounty Connector (ICC). The base case—build scenario represents the land use for year 2010 and current network with the ICC. The future year—no build scenario includes future-year land use along with the base-year network. The future year—build scenario consists of land use forecasts for the year 2030 with all proposed projects as currently contained in the Maryland SHA's Constrained Long Range Plan (CLRP).

A step-by-step process of the methodology used is shown in Figure 3.10. The first step was to prepare the necessary input files to run MSTM. Input files for four scenarios were then created. The next step was to complete the model run and summarize the results. In preparing the model summary, a congested skim matrix was developed to represent congested travel times for each O-D pair. Similarly, corresponding trip matrices were obtained. After summarizing model results for each scenario, reliability ratios for each O-D pair were obtained. Disaggregate travel time savings and travel time reliability savings for all O-D pairs were computed for the base-year and future-year scenarios. In the comparison, average travel times by O-D pair and by time of day, both before and after system enhancements, were

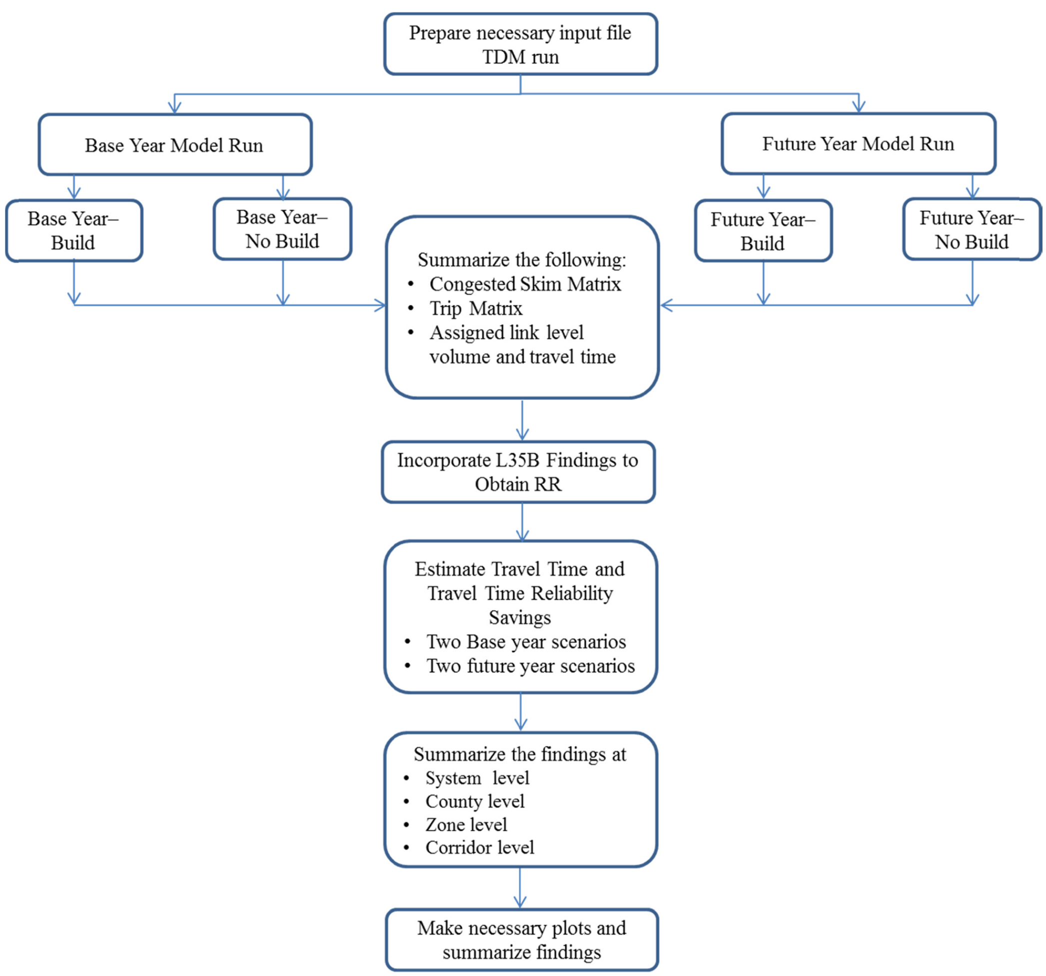



***Figure 3.10. Step-by-step process for incorporating SHRP 2 L35B travel time reliability into MSTM.***

captured. System benefits were estimated based on the resulting improved travel time reliability at the O-D level. The base-year comparison shows benefits resulting from the ICC, and the future-year comparison shows benefits resulting from projects included in CLRP.

The findings of this analysis are summarized at varying geographic levels: statewide, county, zone and corridor. Both travel time savings and travel time reliability savings were computed at these geographic levels. The analysis was conducted for the AM peak period only and by considering all the trips as a medium income group. However, the results can be summarized for other peak periods and by considering the other five income classes included in the MSTM.

## Statewide Findings

Statewide findings were estimated by taking travel time improvements for all O-D pairs when multiplied by corresponding trips. The findings suggest that both the base and future-year scenarios result in savings when compared with their no-build counterparts. Future-year savings are higher than the base year as expected. At the statewide level, travel time reliability savings are approximately 92% of travel time savings for the base year. Table 3.8 shows statewide travel time and travel time reliability savings during peak hours (including AM and PM peak) for a whole year.

## County Level Findings

Travel time savings and travel time reliability savings are plotted at the county level for base (Figure 3.11) and future years (Figure 3.12). County level savings are shown for a typical day in the AM peak period. In the base year, Montgomery and Prince George's counties received higher savings. The majority of these savings can be attributed to the opening of the ICC in the base year under the build scenario. In the future-year scenario, Anne Arundel and Baltimore counties received higher savings as a result of CLRP project implementation in these counties.

*Table 3.8. Statewide Peak Hour Savings for a Year*

| Year | Total Savings | Travel Time (min) | Travel Time ($) |
|---|---|---|---|
| Base Year | Travel Time | 449,915,060 | 104,965,240 |
| | Travel Time Reliability | 416,446,020 | 97,157,160 |
| Future Year | Travel Time | 1,812,587,810 | 422,876,590 |
| | Travel Time Reliability | 1,837,341,380 | 428,651,620 |

## Transportation Analysis Zone Level Findings

Transportation Analysis Zone (TAZ) level findings are shown in Figures 3.13 through 3.16. Base-year findings suggest that zones near the ICC enjoyed higher savings in terms of travel time and travel time reliability values. Future-year findings suggest that the savings are spread over major urban and suburban areas.

Figures 3.13 and 3.15 represent travel time savings in minutes for zones in the following three categories:

- Less than 1 minute;
- Between 1 and 5 minutes; and
- More than 5 minutes.

Figures 3.14 and 3.16 represent travel time reliability value savings in dollars for zones in the following three categories:

- Less than $0.25;
- Between $0.25 and $1; and
- More than $1.

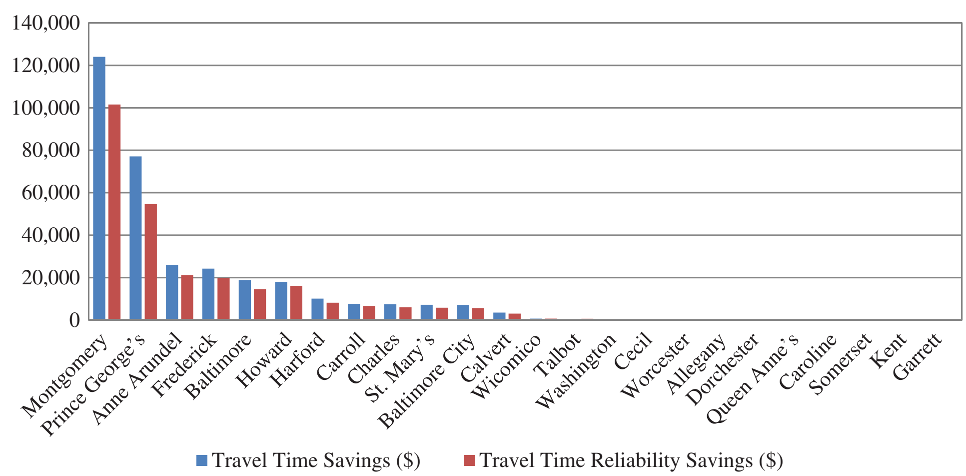



***Figure 3.11. County level savings comparing base year—build with base year—no build.***

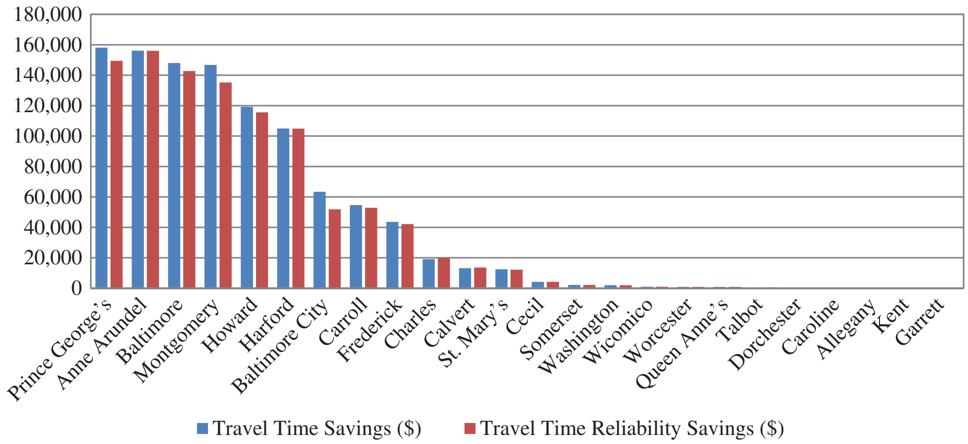



***Figure 3.12. County level savings comparing future year—build with future year—no build.***

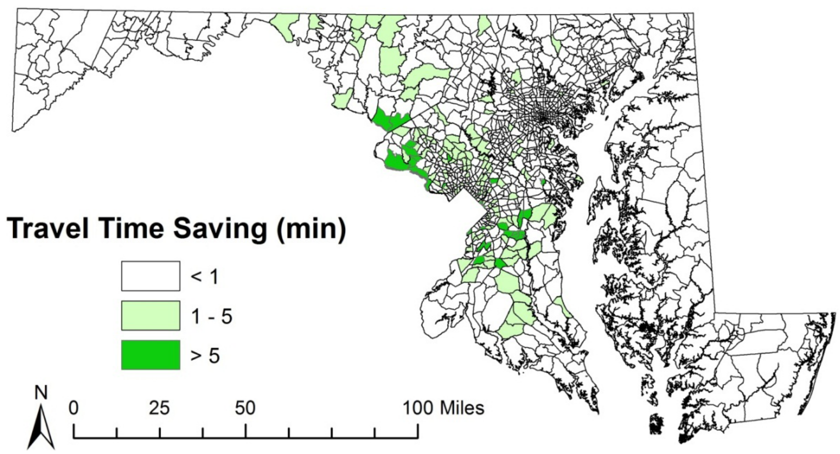



***Figure 3.13. Travel time saving per trip comparing base year—build with base year—no build.***

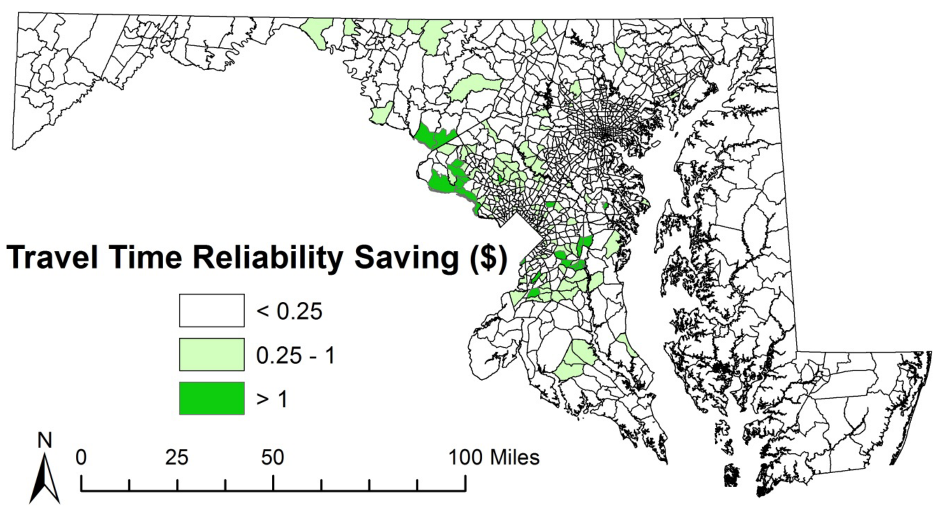



***Figure 3.14. Travel time reliability saving per trip comparing base year—build with base year—no build.***

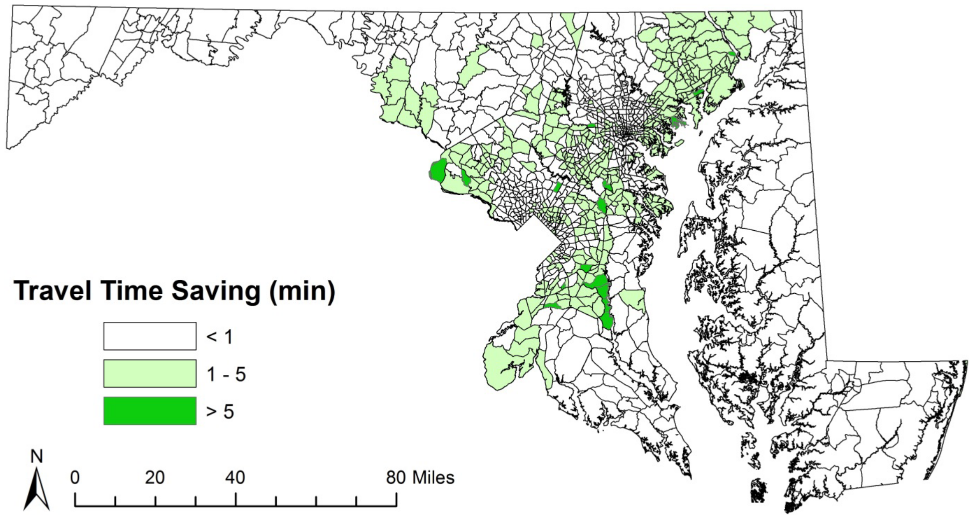



*Figure 3.15. Travel time saving per trip comparing future year—build with future year—no build.*

## Corridor-Level Findings

To illustrate the performance of MSTM in evaluation of savings at the corridor level, a regionally significant corridor on the northwest side of the Capital Beltway was considered. Travel time and travel time reliability savings were determined for the I-270 corridor (Figure 3.17). Table 3.9 shows that, for the I-270 corridor, travel time savings are achieved for both the base and future years when compared with their respective no-build scenarios.

Overall, these results indicate that reliability measures proposed in this study can be integrated into MSTM. For this purpose, four scenarios were considered: base case—no build, base case—build, future year—no build and future year—build. Travel time and travel time reliability savings were shown at the statewide, county, TAZ, and corridor levels. Based on the analysis results presented, savings in travel time reliability appear to be significant at all geographic aggregation levels.

# Results of Presentation to SHA Management

Maryland SHA stakeholders were briefed on project progress throughout the conduct of the research project. The research team was led by a member of SHA's Office of Planning and Preliminary Engineering. A presentation was prepared and made to upper management within SHA to gauge their reaction to

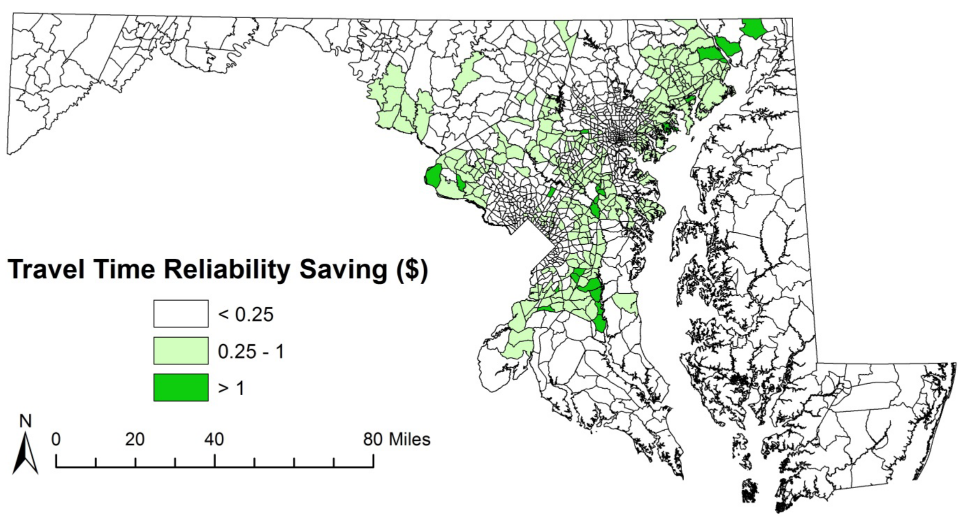



*Figure 3.16. Travel time reliability saving per trip comparing future year—build with future year—no build.*

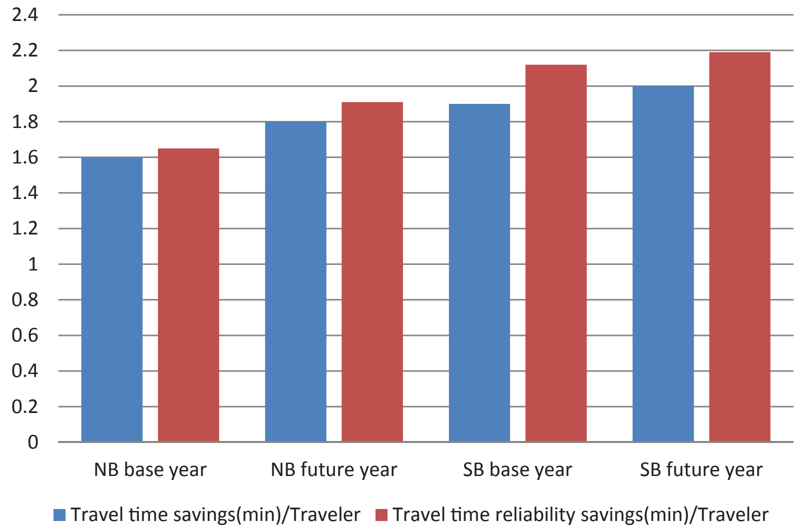



***Figure 3.17. Travel time and travel time reliability savings in minutes per traveler on I-270.***

the findings of this research. The entire presentation used during this meeting is included in Appendix C. What follows is a summary of some of the key points presented and the feedback obtained.

The research team's overall approach to presenting the SHRP 2 L35B project results to SHA management was to (1) explain the travel-time data-driven methodology developed at a high level and NOT get into specific details of its technical development and implementation; and (2) focus on the results of the methodology and its application to both short-term and long-term decision-making processes. A few slides from Appendix C are included here for ready reference in describing the presentation.

The slide in Figure 3.18 was used to explain the underlying analogy for the travel-time data-driven methodology.

If a traveler, based on experience, knows that their morning commute to work takes 10 minutes on average, they might be willing to add 5 minutes to their trip time to avoid the risk of being late to work. This extra 5 minutes has a monetary value and represents the insurance premium that the traveler is willing to pay for this trip. The challenge is to determine this value (the extra 5 minutes in this example) using factors, such as: expected travel time; variations in historical travel time; tolerance of travel time variation; and how differences in expected travel time might impact the traveler's experience.

The following slide in Figure 3.19 was used to provide a high-level explanation of how, essentially, the travel-time data-driven methodology works.

In an attempt to make the complex relatively simple: the proposed travel-time data-driven methodology for estimating

***Table 3.9. I-270 Travel Time and Reliability Results for Four Different Scenarios***

| | I-270 Travel Time (min) | | I-270 RR | | I-270 Travel Time Savings (min/traveler) | | I-270 Travel Time Reliability Savings (min/traveler) | |
|---|---|---|---|---|---|---|---|---|
| **Scenario** | **NB** | **SB** | **NB** | **SB** | **NB** | **SB** | **NB** | **SB** |
| Base Case—No Build | 20.2 | 23.8 | 0.74 | 0.79 | 1.6 | 2.0 | 1.7 | 2.2 |
| Base Case—Build | 18.6 | 21.8 | 0.71 | 0.77 | | | | |
| Future Case—No Build | 21.6 | 25.7 | 0.76 | 0.82 | 1.8 | 2.0 | 1.9 | 2.2 |
| Future Case—Build | 19.8 | 23.7 | 0.73 | 0.79 | | | | |

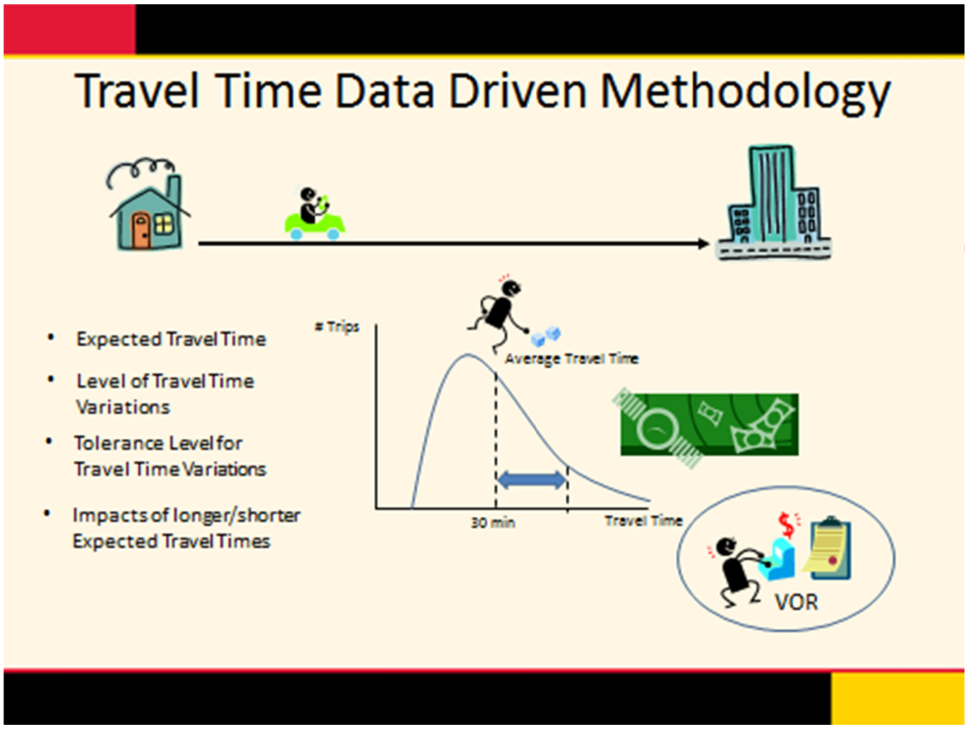



*Figure 3.18. Explanation of the underlying analogy for the travel-time data-driven methodology.*

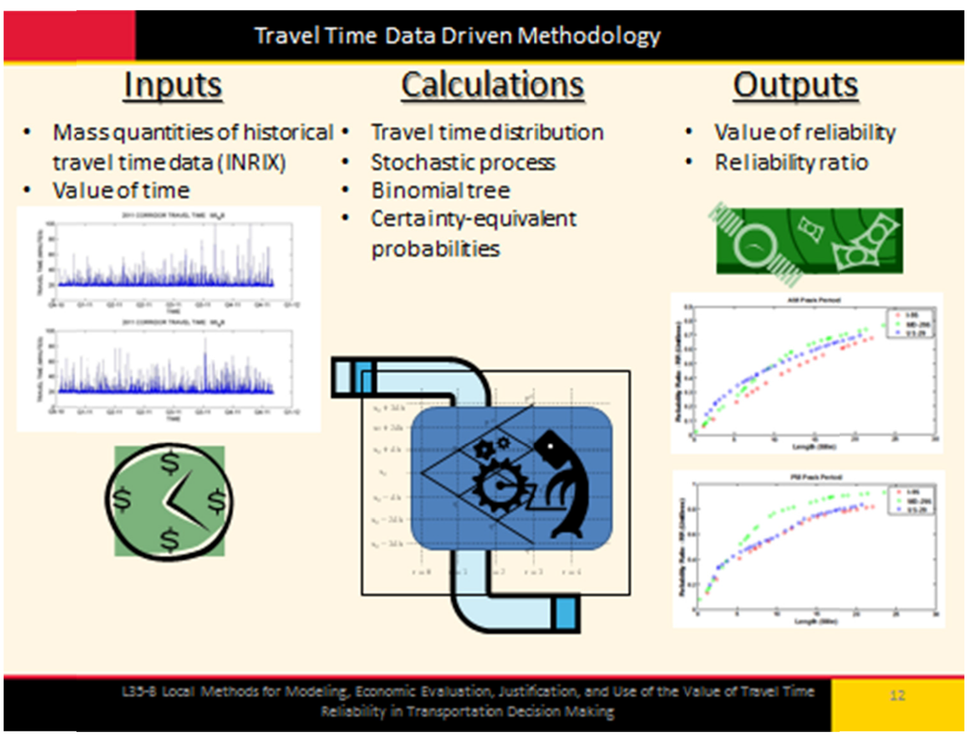



*Figure 3.19. Explanation of how the travel-time data-driven methodology works.*

value of reliability uses large quantities of historical travel time data based on probe data, along with a value of typical/usual travel time (VOTT), and produces a RR along with a value of reliability (VTTR). Discussion of the "calculations" was cursory and an attempt was not made to discuss any technical details. It was mentioned, however, that SHRP 2 would be enlisting outside technical expert reviewers to review the entire methodology developed, its assumptions, and application calculations.

The following slide in Figure 3.20 was used to explain the output of the travel-time data-driven methodology results.

Based on the results obtained from application of the proposed travel-time data-driven methodology, it can be concluded that, during peak hours in congested urban areas, the average reliability ratio ranges between 0.68 and 0.87 derived from MSTM and Census Bureau travel times, respectively (IndexMundi 2013; U.S. DOT 2013). In nonurban areas and at off-peak hours, the average reliability ratio can be taken as 0.52. Therefore, it seems the current value (0.75) is reasonable when reliability of commute travel times during peak hours in congested urban areas is considered.

The slide in Figure 3.21 was used to demonstrate the impact of including a value of reliability (using sensitivity to RR) in SHA's congestion relief project life-cycle BCA selection process (as explained earlier in this chapter).

The slide shows how project rankings are impacted for the top 6 highest ranked projects. If for example, SHA was deciding on priority congestion relief projects with a budget of $15M, not taking into account a value of reliability would likely result in selection of projects ranked 1 (cost is $5.5M) and 2 (cost is $10.9M). Both of these projects involve construction of auxiliary lane extensions; however, project 2 requires construction of a retaining wall, which adds significantly to the cost of the project. Using SHA's current RR of 0.75 results in the project previously ranked 3 jumping into the second ranked slot. This project costs considerably less at $2.6M and involves removing a ramp on the inner loop of I-695 and replacing it with a signal. Finally, if SHA selected a RR value of 0.85 (which is the top of the range of values obtained using the travel-time data-driven methodology), the project previously ranked 4 (cost is $6.5M) jumps into the third ranking. Ultimately, this might mean SHA would choose to do three projects instead of two if the budget was $15M.

SHA was also presented with slides showing the travel time reliability savings at various geographic levels based on construction of the ICC (explained earlier in this chapter). In terms of conclusions, based on the results of this project, the research team expressed the opinion that SHA's current RR of 0.75 is a good, and defensible, estimate based on the literature as well as the proposed travel-time data-driven methodology. That said, while the travel-time data-driven methodology shows significant promise, it does require a rigorous validation of hypotheses underlying the methodological developments as well as validation of application results (see suggested further research).

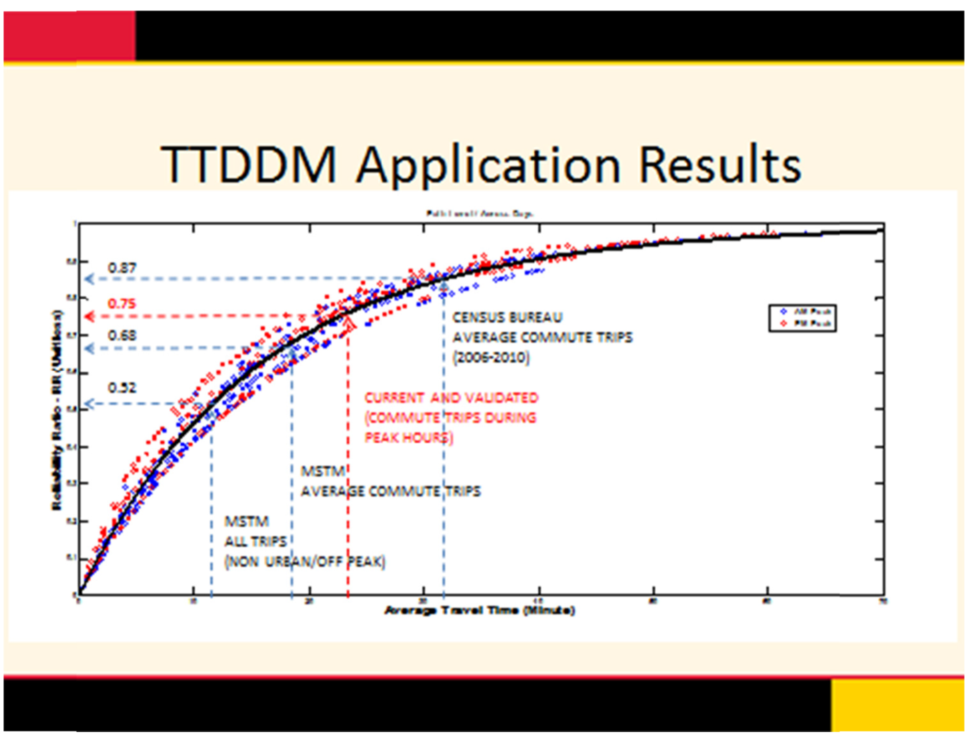



*Figure 3.20. The output of the travel-time data-driven methodology results.*

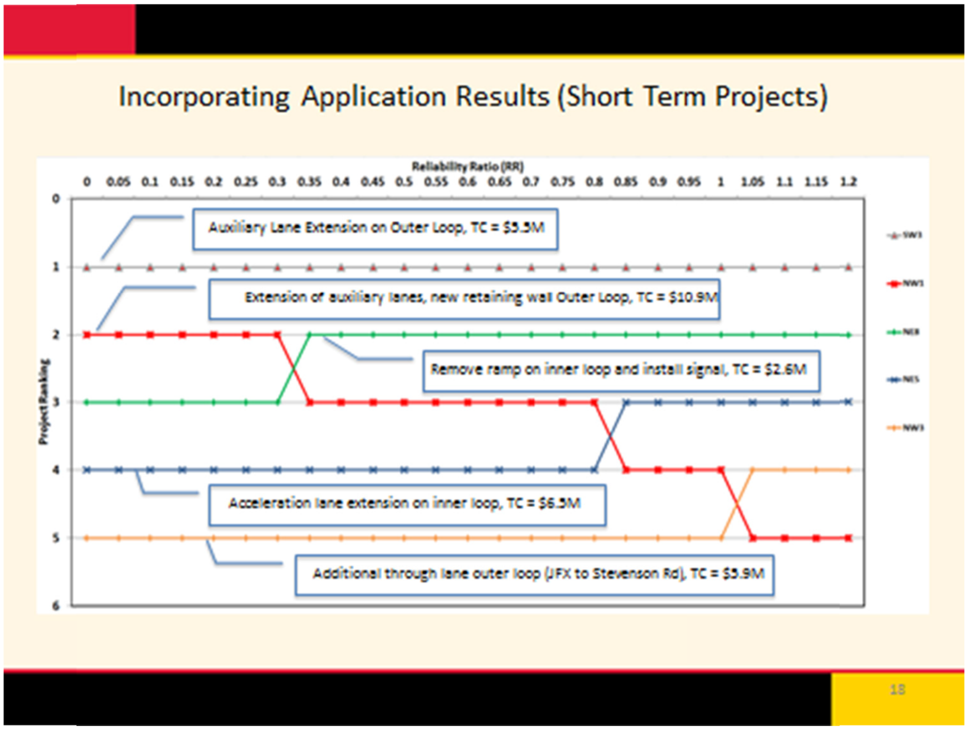



***Figure 3.21. Demonstration of the impact of including a value of reliability in SHA's congestion relief project life-cycle BCA selection process.***

The overall response from SHA, including management, was positive. Interestingly, and perhaps not surprisingly, SHA management did want to learn more about the technical details regarding the travel-time data-driven methodology developed. There was also an interesting discussion, led by SHA management, that perhaps our collective goal should not be focused on "fixing congestion" as that is not necessarily feasible in today's world of financial constraint and other competing issues. Perhaps a better goal is to work toward making the system more reliable; however, the key will be communicating system reliability benefits in a way that is ultimately useful to decision makers. So the goal becomes improving reliability rather than eliminating congestion.

CHAPTER 4

# Conclusions and Suggested Research

## Overall Findings

An overall conclusion from this research suggests that agencies who do not account for VTTR in their BCA processes might be undervaluing project benefits resulting from improvements to trip reliability. Valuation tools and techniques, both existing and newly developed as a result of this research, along with a significant body of literature, provide a basis for incorporating VTTR in an agency's BCA process. While this research project focused on Maryland State Highway as a case study, the information (literature review, data-driven methodology, and application examples) has the potential to help agencies looking to incorporate VTTR in their investment decision processes.

Compared with the recent revealed and stated preference survey-based estimates in the literature, the current RR ratio value of 0.75 used by SHA seems reasonable. Based on the development and application of the data-driven approach to reliability valuation methodology developed under this research, it can be concluded that, in Maryland, during peak hours in congested urban areas, the average RR ranges between 0.68 and 0.87 derived from MSTM and Census Bureau travel times, respectively (IndexMundi 2013; U.S. DOT 2013). In nonurban areas and at off-peak hours, the average RR can be taken as 0.52. Therefore, it seems the current value of 0.75 is reasonable when the reliability of commute travel times during peak hours in congested urban areas is considered.

Given that the Maryland SHA is able to account for the benefit of project-related travel time reliability improvements, a potential next step is to incorporate the results of this project into a future iteration of the Maryland State Highway Mobility Report in the form of costs due to unreliability. Currently, the report includes performance measures based on both congestion (travel time index) and reliability (planning time index). While the statewide cost of congestion is reported, an estimate of the additional cost users incur as a result of a lack of reliability in travel times, and as measured and reported using planning time index, is not currently included. The VTTR estimates obtained from this research could be used to bridge the gap in reporting costs of unreliability in the annual mobility report.

As noted above, this part of the report can help agencies incorporate VTTR into their investment decision processes. Every effort has been made to fully document the data-driven valuation methodology developed under this research to facilitate its transferability to agencies beyond the Maryland SHA. However, doing so at this time would likely require teaming with a university or consultant. A logical next step that would facilitate transferability among agencies, and overall ease of implementation, would be to develop a software tool (or build into an existing performance-measure calculation and reporting tool) that can process the historical travel time data and estimate RR/VTTR using the methodology developed (this is expanded on at the end of the next section). In addition to this suggestion of follow-on work to facilitate the practical application of the results of this research, a number of ideas for future research to build on and enhance the data-driven methodology developed are included in the next section.

## Suggested Future Research

In future research, rigorous validation of hypotheses underlying the methodological developments as well as validation of application results should take the highest priority. The assumptions made regarding travel times following a certain stochastic process (GBM with drift) in this study should be further investigated. It is particularly important to identify a set of stochastic processes with theoretical properties that are consistent with empirical travel time distributions. Note that the proposed valuation method can easily be modified to take into account any other stochastic process to model the projection of travel time distribution over time and into the future. The stochastic volatility family of models (in which GBM is a member), and in particular, the Generalized Auto-Regressive Conditional Heteroskedasticity (GARCH) family of models, are deemed to be potential candidates for this purpose.

The other assumptions regarding the payoff function used in the proposed method needs further validation based on local data. Survey-based measurements of penalties (or rewards) associated with arriving earlier or later than expected can be used as a comparison with the assumed bilinear form of the payoff function and its parameters. In jurisdictions where such survey-based measurements and models are readily available, it is recommended that the VTTR and RR estimates that can be obtained from the proposed data-driven method used in this study be validated against their survey-based counterparts. The payoff function also includes the same valuations for all trip purposes at all times of the day. Research should be conducted on the impact of changes in these factors on the payoff function. In applications regarding future scenario demand levels, average travel times and travel time variability measures are inevitably estimated using some type of model. These available modeling techniques may vary widely by local jurisdiction in terms of their complexity and accuracy. In this study, microsimulation and four-step modeling techniques were used for short-term and long-term evaluation of the impact of improvements on travel time reliability savings, respectively. Other traffic analysis techniques, as simple as sketch planning or as complicated as Dynamic Traffic Assignment (DTA), may be used in practice for this purpose. Given data availability, it is highly recommended that the effectiveness and accuracy of these modeling tools in recreating the needed measures of travel time variation and reliability be further investigated in real-world cases.

Interactions between trip characteristics, traveler decision making, and travel time reliability valuation should be further investigated. Trip purpose (commute versus noncommute), mode (auto versus freight), facility type (freeway versus arterial), income level, trip distance, geography (urban versus rural), geometry (number of travel lanes) and presence of alternatives (e.g., mode, route, trip time) are among the factors that conceivably have a direct impact on the value of travel time reliability. In the context of the proposed method developed in this study, the impact of these factors on VTTR estimation can be traced through their impact on the VOTT estimate, travel time variability (model specific parameters), and terminal payoff function characterizations.

Different methods can be potentially used to aggregate travel time data. The respective impact of these aggregation methods on travel time variability and reliability valuation could be significant. In this study an instantaneous travel time aggregation method is used to estimate path travel times based on link travel times. It is conceivable that more elaborate path travel time estimation methods (e.g., trajectory construction-based models), will result in more accurate travel time estimates for long distance trips. Also, in this study 1-minute travel times are used. At this level, travel time data provides a very high level of resolution that essentially captures much of the variation in travel time experienced by users. However, it is possible that other jurisdictions may not have access to data at this resolution level, or they may decide to perform some temporal aggregation to avoid higher computational costs. It is recommended that in the future, the sensitivity of VTTR estimates to the accuracy and granularity of path travel time estimates be investigated.

From a practical perspective, it is important that both spatial and temporal transferability of VTTR and RR models and estimates be investigated. The result would inform decisions as to how often the analysis needs to be repeated considering recent data, and whether or not similar (maybe nearby) jurisdictions need to perform the analysis using their respective local data. One potential outcome of such a study could be a set of recommended VTTR and RR values that can be used by local jurisdictions where access to accurate speed data and other resources needed to perform the proposed data-driven analysis is limited.

Finally, a logical next step would be to develop a software tool to process the historical travel time data and to automate the estimation of VTTR and RR values. The software tool should provide the opportunity to perform hypothesis testing and to calibrate appropriate stochastic process parameters. This tool will also facilitate the sensitivity analysis through enabling seamless variation of different assumptions regarding the time series process, payoff function specifications, and estimation parameters. Additionally, the tool should provide the capability to perform sensitivity analysis on all assumptions that go into the project benefits quantification.

# References: Part 1


Asensio, J., and Matas, A. 2008. Commuters' Valuation of Travel Time Variability. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 44, 1074–1085.

Bhat, C., and Sardesai, R. 2006. The Impact of Stop-Making and Travel Time Reliability on Commute Mode Choice. *Transportation Research Part B: Methodological,* Vol. 40, 709–730.

Black, I., and Towriss, J. 1993. *Demand Effects of Travel Time Reliability.* Technical Report. Centre for Logistics and Transportation, Cranfield Institute of Technology, United Kingdom.

Borjesson, M. 2009. Modelling the Preference for Scheduled and Unexpected Delays. *Journal of Choice Modelling,* 2(1), 29–50.

Brownstone, D., and K. A. Small. 2005. Valuing Time and Reliability: Assessing the Evidence from Road Pricing Demonstrations. *Transportation Research Part A: Policy and Practice,* Vol. 39, pp. 279–293.

Cambridge Systematics. 2008. *Integrated Corridor Management Analysis, Modeling, and Simulation Experimental Plan for the Test Corridor.* Report No. FHWA-JPO-08-035EDL 14415.

Cambridge Systematics and ICF International. April 26, 2012. *Synthesis Report & Workshop Working Paper.* SHRP 2 Workshop on the Value of Travel Time Reliability.

Carrion, C., and Levinson, D. 2010. Value of Reliability: High Occupancy Toll Lanes, General Purpose Lanes, and Arterials. In *Conference Proceedings of 4th International Symposium on Transportation Network Reliability,* Minneapolis, Minn.

Carrion, C., and Levinson, D. 2011. A Model of Bridge Choice Across the Mississippi River in Minneapolis. In *Network Reliability in Practice: Selected Papers From the Fourth International Symposium on Transportation Network Reliability* (D. Levinson, H. Liu, and M. Bell, eds.), Springer, Chapter 8, pp. 115–129.

Carrion, C. and Levinson, D. 2012. Value of Travel Time Reliability: A Review of Current Evidence. *Transportation Research Part A: Policy and Practice,* Vol. 46, pp. 720–741.

Chang, G.-L. 2011. *Performance Evaluation of CHART: An Incident Management Program,* Report prepared for Maryland State Highway Administration, University of Maryland.

Cirillo, C., Liu, Y., and Serulle, U. January 2014. *Travel Time Reliability of Road Transportation Systems: Methods and Case Studies.* White Paper.

Cohen, H., and Southworth, F. 1999. *On the Measurement and Valuation of Travel Time Variability Due to Incidents on Freeways.* http://ntl.bts.gov/lib/7000/7500/7598/2cohen.pdf

Concas, S., and Kolpakov, A. January 2009. *Synthesis of Research on Value of Time and Value of Reliability.* Report No. BD 549-37.

De Jong, G. 2000. Value of Freight Travel Time Savings. In *Handbook of Transport Modeling* (Hensher D. A. and K. J. Button, eds.) Elsevier.

De Jong, G., Tseng, Y., Kouwenhoven, M., Verhoef, E., and Bates, J. 2007. *The Value of Travel Time and Travel Time Reliability.* Technical Report. The Netherlands Ministry of Transport, Public Works and Water Management.

Delache, X. 2009. Cost Benefits Analysis Applied to Reliability Policies in France. Presented at International Meeting on Value of Travel Time Reliability and Cost-Benefit Analysis, Vancouver, B.C., Canada.

Department for Transport, Transport Appraisal and Strategic Modelling Division. 2014. Transport Analysis Guidance (TAG) UNIT A1.3 User and Provider Impacts. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/313222/webtag-tag-unit-a1-3-user-and-provider-impacts.pdf

Dowling, R., Skabardonis, A., Carroll, M., and Wang, Z. 2004. *Methodology for Measuring Recurrent and Non-Recurrent Traffic Congestion.* Presented at the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C.

Eliasson, J. 2009. Reliability in Swedish CBA—Current Practice and What Needs to be Done. Presented at the International Meeting on Value of Travel Time Reliability and Cost-Benefit Analysis, Vancouver, B.C., Canada.

FHWA. 2013. *Highway Economic Requirements System.* http://www.fhwa.dot.gov/infrastructure/asstmgmt/hersindex.cfm

FHWA. 2014. *Intelligent Transportation System Deployment Analysis System (IDAS).* http://www.fhwa.dot.gov/research/deployment/idas.cfm

Fosgerau, M., and Karlström, A. 2010. The Value of Reliability. *Transportation Research Part B: Methodological,* Vol. 44, No. 1, pp. 38–49.

Fukuda, D. 2009. Reliability Valuation in Japan. Presented at International Meeting on Value of Travel Time Reliability and Cost-Benefit Analysis, Vancouver, B.C., Canada.

Ghosh, A. 2001. Valuing Time and Reliability: Commuters' Mode Choice from a Real Time Congestion Pricing Experiment. PhD dissertation. University of California, Irvine.

Hollander, Y. 2006. Direct Versus Indirect Models for the Effects of Unreliability. *Transportation Research Part A: Policy and Practice,* Vol. 40, 699–711.

IndexMundi. http://www.indexmundi.com/facts/united-states/quick-facts/maryland/average-commute-time#map. Accessed 2013.

International Transport Forum, Joint Transport Research Centre of the OECD and the ITF. 2010. *Surface Transport Networks: Improving Reliability and Levels of Service,* http://www.internationaltransportforum.org/pub/pdf/10Reliability.pdf

International Transport Forum. 2012. Policy Brief: Making Reliability Part of Transport Policy, April.

KiM Netherlands Institute for Transport Policy Analysis. November 2013. *The Social Value of Shorter and More Reliable Travel Times.* Report. Ministry of Infrastructure and the Environment.

Koskenoja, P. 1996. The Effect of Unreliable Commuting Time on Commuter Preferences. PhD dissertation. University of California, Irvine.

Levinson, D., and Smalkoski, B. 2003. *Value of Time for Commercial Vehicle Operators in Minnesota.* TRB International Symposium on Road Pricing, Key Biscayne, Fla.

Li, Z., Hensher, D., and Rose, J. 2010. Willingness to Pay for Travel Time Reliability in Passenger Transport: A Review and Some New Empirical Evidence. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 46, 384–403.

Liu, H., Recker, W., and Chen, A. 2004. Uncovering the Contribution of Travel Time Reliability to Dynamic Route Choice Using Real-Time Loop Data. *Transportation Research Part A: Policy and Practice,* Vol. 38, 435–453.

Liu, H., He, X., and Recker, W. 2007. Estimation of the Time-Dependency of Values of Travel Time and Its Reliability from Loop Detector Data. *Transportation Research Part B: Methodological,* Vol. 41, 448–461.

Mahapatra, S., Wolniak, M., Sadabadi, K. F., Beckett, E., and Jacobs, T. September 2013. *Maryland State Highway 2013 Mobility Report—2nd Edition.* Maryland Department of Transportation, Baltimore.

Maryland Department of Transportation. 2009. *2009 Maryland Transportation Plan.* http://www.mdot.maryland.gov/Office_of_Planning_and_Capital_Programming/Plans_Programs_Reports/Reports/MTP/2009MTP.pdf

Maryland Department of Transportation, State Highway Administration. 2011. *Fiscal Year 2011 Annual Report.* http://sha.md.gov/OC/Annual_FY11_Report.pdf

Maryland State Highway Administration. June 2011. *CHART Planning & Programming Process,* Office of CHART and ITS Development.

Maryland State Highway Administration. June 2012. *Maryland State Highway Mobility Report.* Maryland Department of Transportation, Baltimore.

National Center for Smart Growth and Parsons Brinckerhoff. June 2011. *Maryland Statewide Transportation Model User's Guide: Draft Final Report.* Report for Maryland State Highway Administration.

Pu, W., Mahapatra, S., Tadayon, M., and Simpson, D. N. August 2013. *Identifying Net Effect of Highway Project in Before-and-After Evaluation.* Paper submitted for presentation at the 93rd Annual Meeting of the Transportation Research Board, Washington, D.C.

Senna, L. 1994. The Influence of Travel Time Variability on the Value of Time. *Transportation,* Vol. 21, 203–228.

Shires, J., and De Jong, G. 2009. An International Meta-Analysis of Value of Travel Time Savings. *Evaluation and Program Planning,* Vol. 32, 315–325.

SHRP 2. 2010a. *SHRP 2 Draft Reports for Projects C10A and C10B, Partnership to Develop an Integrated, Advanced Travel Demand Model and a Fine-Grained, Time-Sensitive Network,* Transportation Research Board of the National Academies, Washington, D.C.

SHRP 2. 2010b. *SHRP 2 Draft Report C11: Development of Tools for Assessing Wider Economic Benefits of Transportation,* Transportation Research Board of the National Academies, Washington, D.C.

SHRP 2. 2012. *SHRP 2 Draft Report L11: Evaluating Alternative Operations Strategies to Improve Travel Time Reliability.* Transportation Research Board of the National Academies, Washington, D.C.

SHRP 2. 2013a. *SHRP 2 Draft Report C04: Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand,* Transportation Research Board of the National Academies, Washington, D.C.

SHRP 2. 2013b. *SHRP 2 Draft Report L04: Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools.* Transportation Research Board of the National Academies, Washington, D.C.

SHRP 2. 2013c. *SHRP 2 Draft Report L05: Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes.* Transportation Research Board of the National Academies, Washington, D.C. http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2prepubL05Guide.pdf

Significance, VU University Amsterdam and John Bates Services in collaboration with TNO, NEA, TNS NIPO and PanelClix. November 2013. *Values of Time and Reliability in Passenger and Freight Transport in The Netherlands.* Report for the Ministry of Infrastructure and the Environment. Project 08064, Revised Final Version.

Small, K., Noland, R., and Koskenoja, P. 1995. *Socio-Economic Attributes and Impacts of Travel Reliability: A Stated Preference Approach.* California PATH Research Report No. UCB-ITS-PRR-95-36.

Small, K., Noland, R., Chu, X., and Lewis, D. 1999. *Valuation of Travel-Time Savings and Predictability in Congested Conditions for Highway User-Cost Estimation.* National Cooperative Highway Research Program Report No. 431.

Small, K., Winston, C., and Yan, J. 2005. Uncovering the Distribution of Motorists' Preferences for Travel Time and Reliability. *Econometrica,* Vol. 73, 1367–1382.

Taylor, Michael A. P. 2009. Reliability and Benefit–Cost Analysis in Australia and New Zealand. Presented at the International Meeting on Value of Travel Time Reliability and Cost-Benefit Analysis, Vancouver, B.C., Canada.

Tilahun, N., and Levinson, D. 2010. A Moment of Time: Reliability in Route Choice Using Stated Preference. *Journal of Intelligent Transportation Systems,* Vol. 14, 179–187.

TransportationEconomics.org 2010. http://bca.transportationeconomics.org/benefits/travel-time/categories-of-travel-time

Transportation Research Board of the National Academies. October 15–16, 2009. *International Meeting on Value of Travel Time Reliability and Cost-Benefit Analysis.* Jointly organized by SHRP 2 of the Transportation Research Board, Washington, D.C., and the Joint Transport Research Centre, Vancouver, B.C., Canada.

Transportation Research Board of the National Academies. 2014. http://www.trb.org/StrategicHighwayResearchProgram2SHRP2/General.aspx

Tseng, Y., Ubbels, B., and Verhoef, E. 2005. "Value of Time, Schedule Delay and Reliability. Estimation Results of a Stated Choice Experiment among Dutch Commuters Facing Congestion," European Regional Science Association Congress.

University of Florida, Transportation Research Center. April 2007. *Travel Time Reliability and Truck Level of Service on the Strategic Intermodal System.* Final report to Florida Department of Transportation.

U.S. Department of Transportation, Research and Innovative Technology Administration (RITA). *State Transportation Statistics.* Washington, D.C., 2013. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/state_transportation_statistics/state_transportation_statistics_2013/index.html/chapter4/table4_1

Yan, J. 2002. Heterogeneity in Motorists' Preferences for Travel Time and Time Reliability: Empirical Finding from Multiple Survey Data Sets and its Policy Implications. PhD thesis, University of California, Irvine.

Yusufzyanova, D., and Zhang, L. January 2011. *Multi-Modal and Multi-Jurisdictional Transportation Investment Decision Making: The Case of the Washington DC–Baltimore Region.* Paper submitted to TRB for publication.

APPENDIX A

# Overview of Maryland Department of Transportation Planning

The Maryland Department of Transportation (MDOT) is one of the state's largest agencies, with nearly 9,000 employees committed to delivering a balanced and sustainable multimodal transportation system for all Maryland's residents and businesses. As a truly multimodal transportation agency, MDOT is responsible for coordinating statewide transportation planning activities across all methods of transportation, including highways, tunnels, bridges, railways, rail transit, buses, ports, airports, bike paths, sidewalks, and trails, as well as driver services. MDOT provides oversight of, and coordinates with, five administrations that have unique functional responsibilities for the transportation facilities and services in Maryland as shown in Figure A.1.

## State Report on Transportation

Each year MDOT publishes the State Report on Transportation (SRT). The SRT contains three important documents: the Maryland Transportation Plan (MTP), the Consolidated Transportation Program (CTP), and the annual Attainment Report (AR) on Transportation System Performance. Figure A.2 gives a visual example of how it is compiled.

## Maryland Transportation Plan

The MTP is a 20-year vision for transportation in Maryland. It outlines the state's transportation policies and priorities and helps guide statewide investment decisions across all methods of transportation. The MTP is one component of the annual State Report on Transportation, which also includes the CTP and the AR. The CTP is Maryland's six-year capital budget for transportation projects. The annual AR tracks MDOT's progress toward attaining the goals and objectives of the MTP using outcome-oriented performance measures.

The current MTP was completed in 2009 (MDOT, 2009). The five stated goals of the current MTP include

1. Quality of Service—enhances users' access to and positive experience with all MDOT transportation services.
2. Safety and Security—provide transportation assets that maximize personal safety and security in all situations.
3. System Preservation and Performance—protect Maryland's investment in its transportation system through strategies to preserve existing assets and maximize the efficient use of resources and infrastructure.
4. Environmental Stewardship—develops transportation policies and initiatives that protect the natural, community, and historic resources of the state and that encourage development areas that are best able to support growth.
5. Connectivity to Daily Life—supports continued economic growth in the state through strategic investments in a balanced, multimodal transportation system.

The goal of improving quality of service basically reflects improvements in accessibility and mobility. This should include reduction in travel time or delay, or increase in travel time reliability for non-motorized travelers, private vehicle users, transit users, and freight/commercial users. Figure A.3 presents the current MTP milestones.

Over time, changes to Maryland's population, economy, and environment will result in far-reaching effects on the transportation system. The picture of transportation in Maryland in 20 years may look quite different from today's picture. Though not a comprehensive list of the challenges that MDOT will face in the coming years, the following critical issues are some of the most important issues that will shape the decisions made by MDOT, its modal administrations, and the Maryland Transportation Authority (MDTA). The MTP provides a path to help MDOT address these challenges in the future. They are

- Transportation and the economy
- Freight demand and infrastructure capacity
- Planning for development

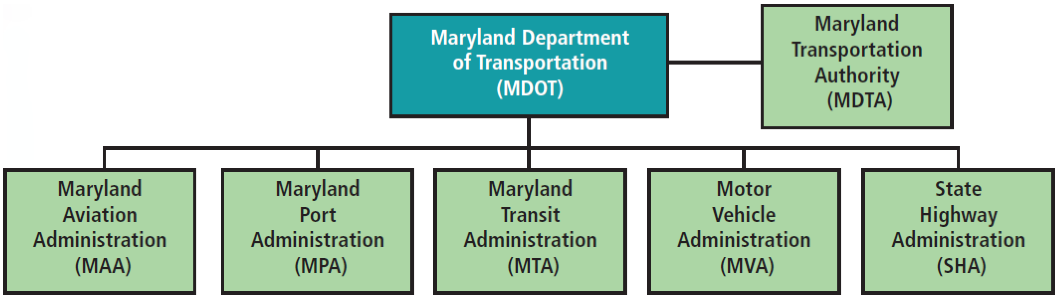



***Figure A.1. Maryland Department of Transportation with its modal administrations.***

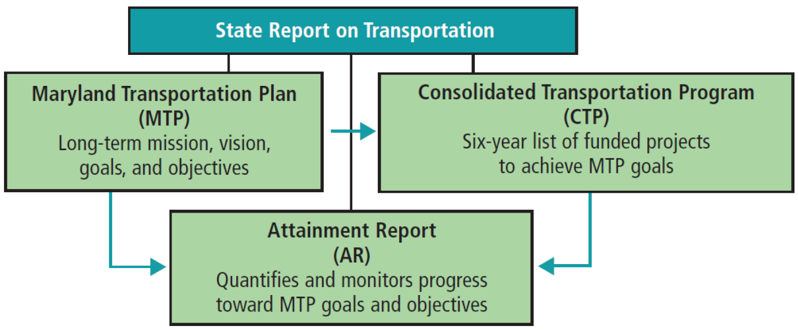



***Figure A.2. Components of the State Report on Transportation.***

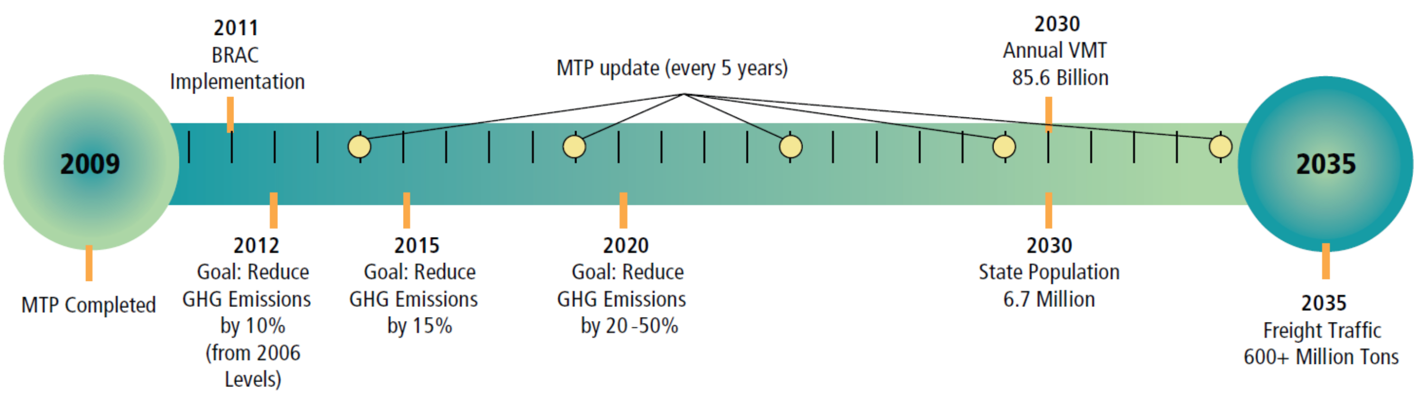



***Figure A.3. Current Maryland Transportation Plan milestones.***

- Transportation and the environment
- Transportation needs outpacing funding resources
- Transportation-related fatalities and injuries

## Maryland Department of Transportation Budget Allocation

MDOT has a somewhat unusual system for funding transportation projects. The state's Transportation Trust Fund (TTF) is a unified pot of money that provides MDOT the flexibility to fund high-priority projects across the state regardless of transportation modes (Yusufzyanova et al., 2011). Local roads in Maryland are controlled and maintained by cities and counties. Also, MDOT provides Maryland's entire share of funding for the regional transit system in the D.C. area known as the Washington Metropolitan Area Transit Authority (WMATA). Figure A.4 illustrates MDOT's TTF allocation between jurisdictions and modes in the state. TTF is first divided into separate funds to meet different transportation needs categories (e.g., maintenance, capital programming) and then allocated to different modal agencies, where it is then subject to the investment process of the modal agencies.

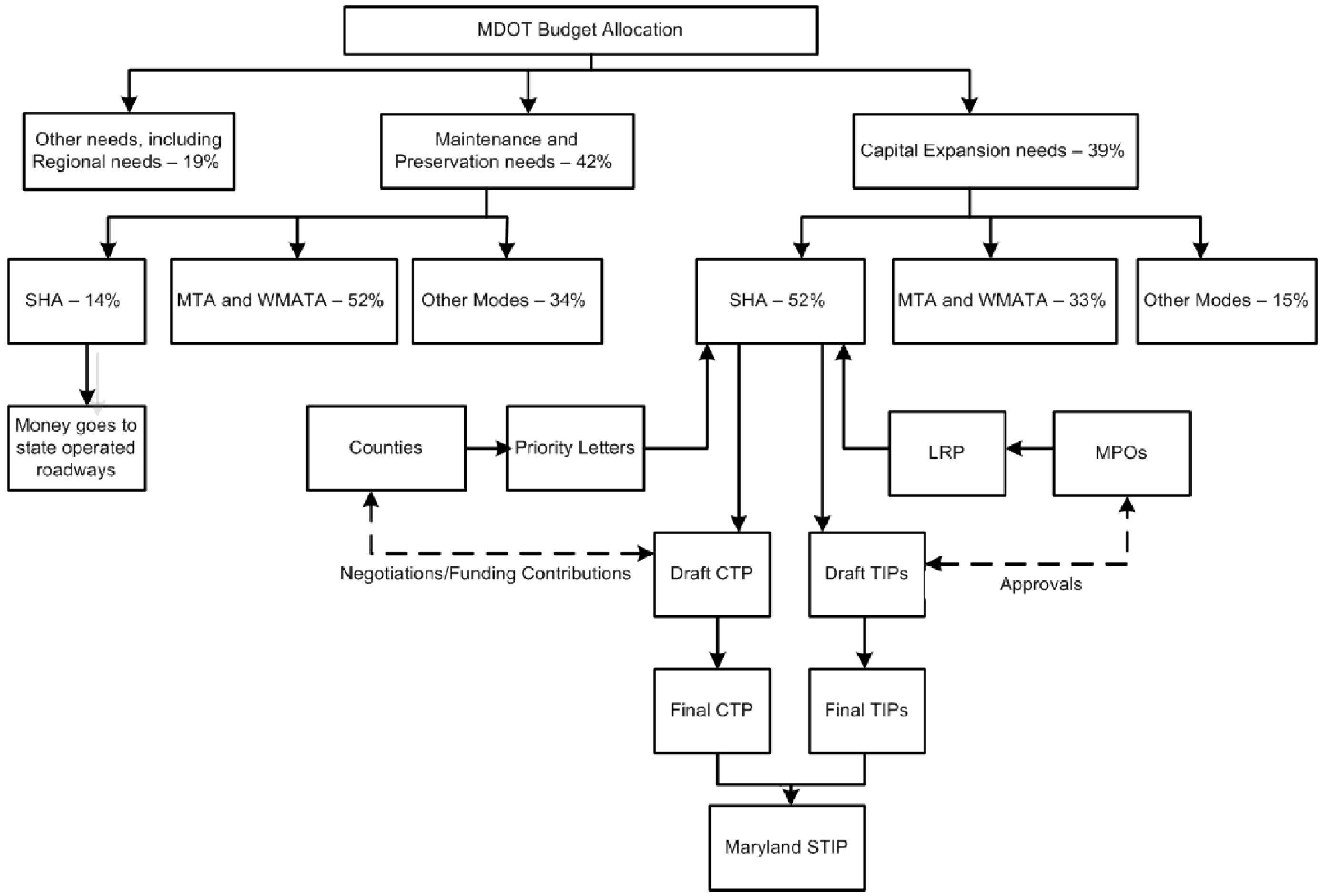



***Figure A.4. MDOT's TTF allocation between jurisdictions and modes in the state. (Given percentages are FY 2009 budget allocation (may vary year to year).)***

## Overview of SHA Investment Decision-Making Process

The Maryland State Highway Administration receives highway transportation funds from MDOT, and works with Metropolitan Planning Organizations (MPOs) and local jurisdictions to allocate funds to meet highway preservation and capital programming needs. In the last two decades, system preservation projects have received a higher and higher share of SHA's transportation funds due to aging infrastructure, and this trend is likely to continue in the future. The Administration identifies system maintenance and preservation needs through an internal technical evaluation process, and has created a large number of funding categories for different preservation and maintenance needs. For instance, SHA performs technical evaluation of pavement and bridge conditions every year, and has set the goal of keeping 84% of pavements under "acceptable conditions." While pavement and bridge maintenance consumes the majority of SHA's system preservation budget, there are also 24 smaller funding categories dedicated to specific needs including drainage, traffic signs, and community improvement. For capital improvement and system expansion projects, SHA coordinates with six MPOs and local jurisdictions (through a priority-letter process discussed below).

The SHA transportation investment process centers on MPO-level transportation improvement programs (TIPs) and the statewide Consolidated Transportation Program (CTP). TIPs represent projects within the boundary of each MPO, and SHA provides technical assistance with those projects on request. TIPs consist of projects funded by federal money and matching state/local contributions. The CTP is a six-year program that is financially constrained by the Maryland Transportation Trust Fund. Figure A.5 shows the timeline for the CTP development process. There is a financially unconstrained predecessor to the CTP, often referred to as the 20-year state Highway Needs Inventory (HNI). The HNI is a technical document (based on performance/condition monitoring and travel demand forecasts) that identifies all required highway improvements as well as safety and structural problems on the existing highway facilities. Usually, only "serious" projects from the HNI undergo detailed engineering planning

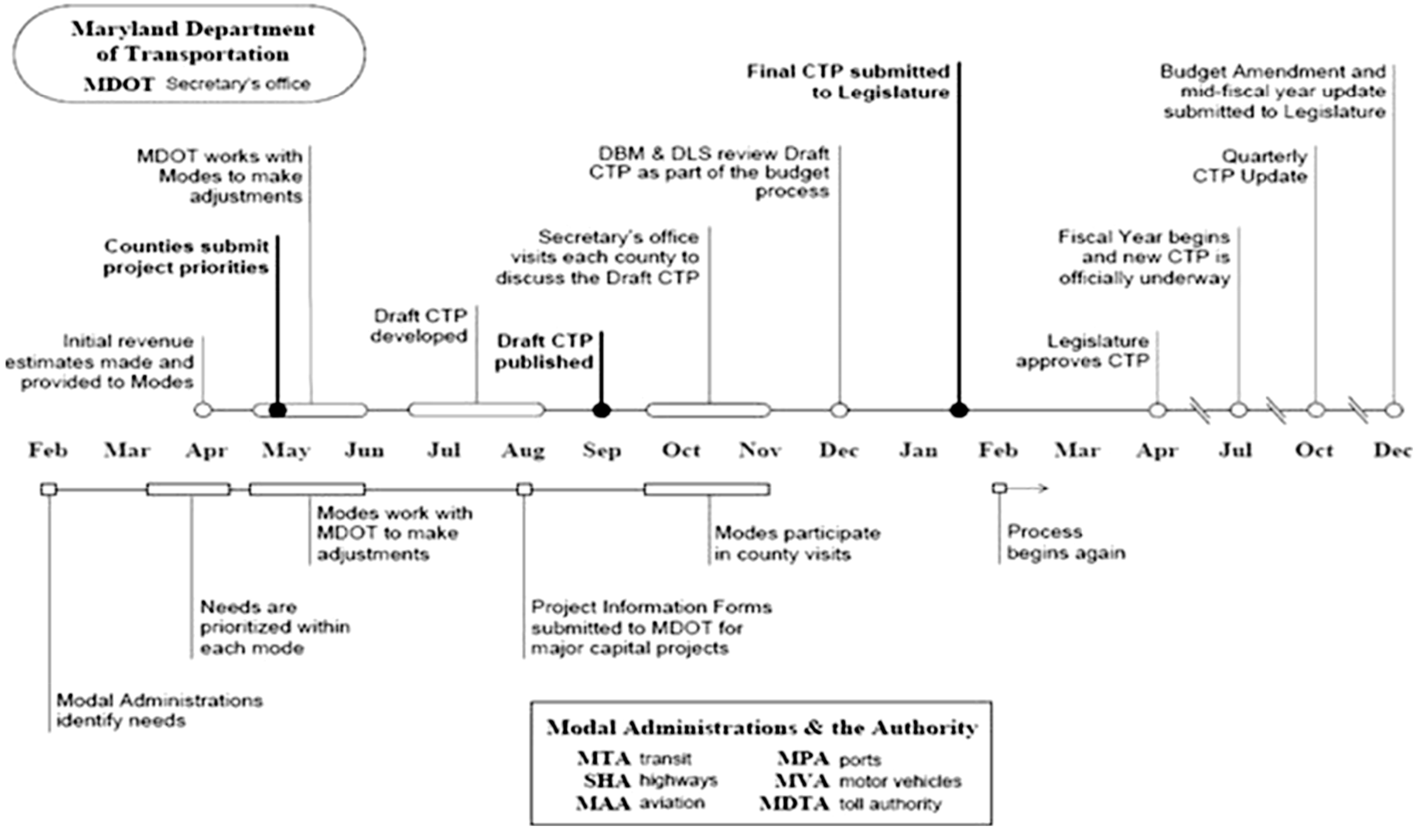



*Figure A.5. Timeline for CTP development process.*

phases and cost estimation procedures. The HNI lists only major capital improvement projects (i.e., no system preservation projects), and is the main source of candidate projects for the SHA transportation investment process. Another source of candidate projects is the priority letters submitted to SHA by individual counties in Maryland. Priority letters represent each county's internal ranking of projects based on local needs and local inputs.

All candidate projects for capital improvement from HNI and county priority letters are evaluated by SHA planners based on three main investment criteria: safety, congestion mitigation, and support for economic development, though there is no formal quantitative evaluation procedure. Priority letters should detail how each priority project supports the goals of the Maryland Transportation Plan and are consistent with the county's land use plan goals. MDOT provides a two-page project questionnaire that summarizes all the needed information about each project (note that the questionnaire specifically mentions travel time reliability as an objective under the goal of improved quality of service).

NEPA (National Environmental Policy Act) and political considerations also play a role in this prioritization process, though the actual influence of these two factors can only be analyzed on a project-by-project basis. Although there is a formal procedure for SHA to discuss project prioritization with counties each fall (known as the "fall county tour" during which MDOT and SHA engineers and planners visit each county and hold public meetings; there are also meetings between SHA and local jurisdiction representatives before the tour), it is possible that a county may not get any high-priority projects for the county funded by SHA. If a project proposed by a county meets all SHA requirements but does not receive enough federal or state funding to be included into the CTP, the county may "come to the table" and share the cost with SHA. Typically, only the counties with high levels of economic development (e.g., Montgomery and Howard counties) participate financially as project sponsors. After needs-based analysis and negotiations with counties are completed, SHA submits the draft CTP each year to the MDOT secretary, which may be revised and then submitted to the Maryland state legislature for possible further revisions and budget approval. Revisions to CTP at these later stages often originate from political influences and changes in budgetary situations.

The complete high-level process for the SHA investment process, including interactions with counties and MPOs, is shown in Figure A.6.

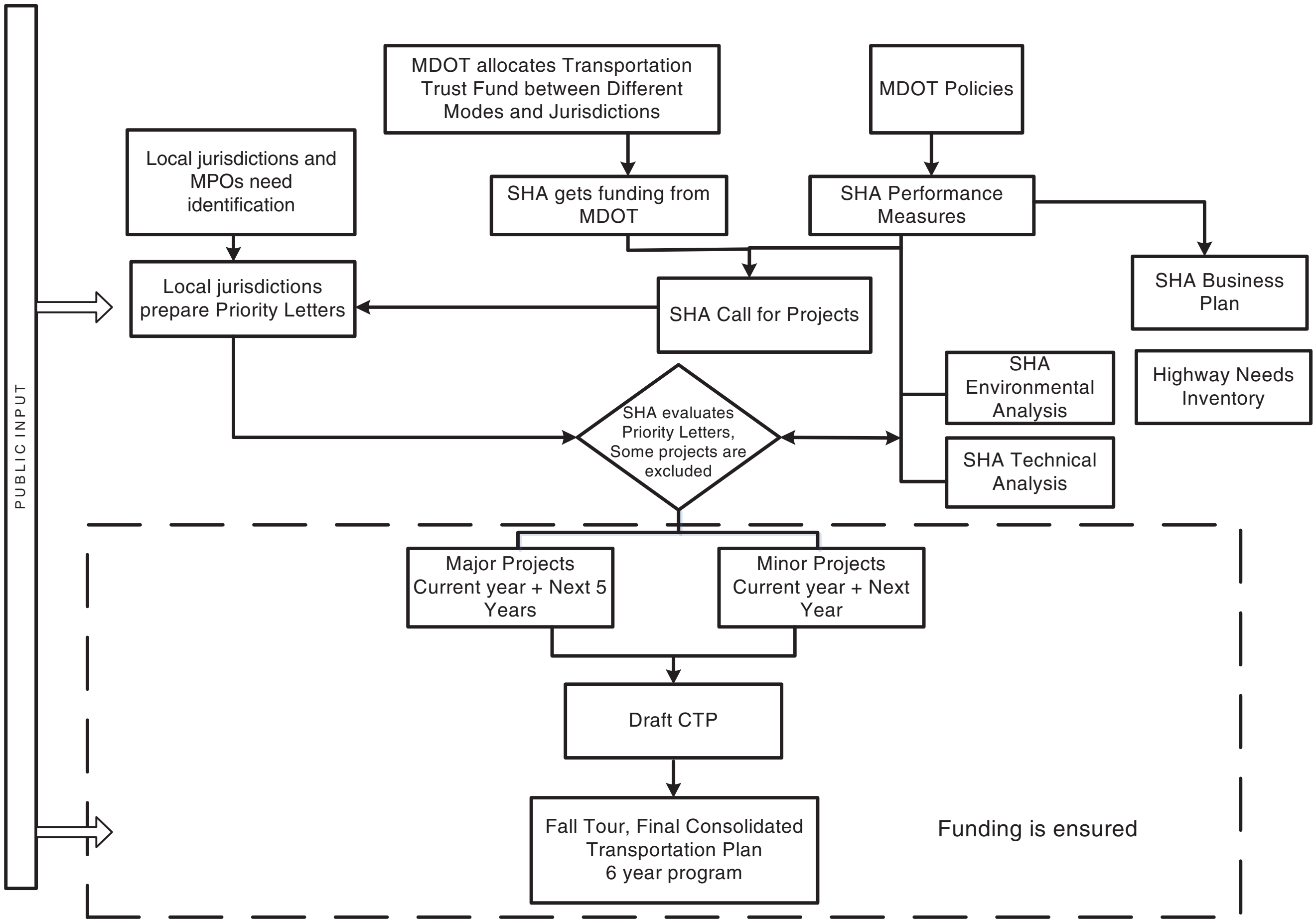



***Figure A.6. High-level process for SHA investment process, which includes interactions with counties and with MPOs.***

## Maryland State Highway Administration Budget Allocation—Example from FY2011

SHA's annual expenditure can be divided into two distinct areas with each area further breaking down into three main categories:

- Capital ($738.3M)
  - Construction ($634.3M)
  - County and Municipality ($98.3M)
  - IT Development ($5.6M)
- Operating ($409.7M)
  - Maintenance ($236.7M)
  - County and Municipality ($157.5M)
  - Highway Safety ($15.5M)

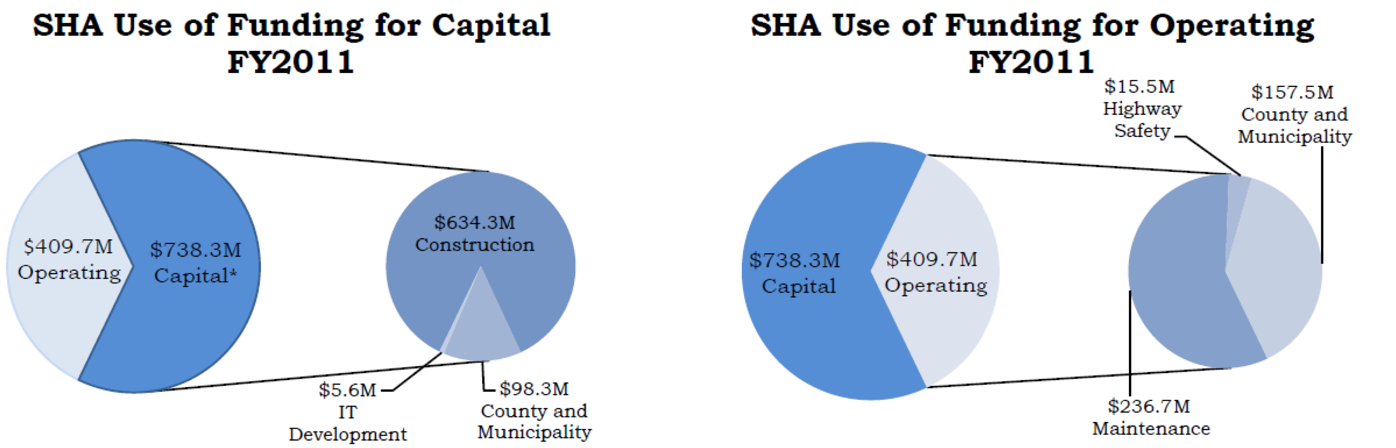
The numbers within parenthesis indicate SHA's expenditures in each category during FY2011 as reported in the Maryland SHA Annual Report (MDOT SHA, 2011).

The pair of pie charts and the table in Figure A.7 further illustrates how SHA use of funding for capital and operating projects has been apportioned among various programs.

## CHART (Operations & Management) Planning and Programming Process

After several years of experience in deploying intelligent transportation system (ITS) technology, the Maryland SHA has established a process within its CHART program for planning, programming, designing, building, operating, and maintaining ITS to provide benefits to its customers (Maryland SHA, June 2011). What follows is a high-level description of the planning and programming portion of the CHART program's deployment process.

Planning is the initial step within the CHART ITS project process. Once an operational need is established for a particular CHART project, it is first planned using inputs from all relative users and stakeholders, and then the appropriate




| Capital Construction Funds Spent | FY2011 | Operating Maintenance Funds Spent | FY2011 |
|---|---|---|---|
| Major Projects (planning, design, right of way and construction phases) | $127.6M | Routine Maintenance | $99.8M |
| Bridge Rehabilitation Projects | $101.3M | Bridge Maintenance | $10.2M |
| Pavement Resurfacing/Rehabilitation Projects | $132.8M | Environmental Design and Compliance | $3.1M |
| Safety-related Infrastructure Projects | $72.2 M | Traffic/CHART Operations | $16.7M |
| Multi-modal Access Projects | $23.8M | Winter Operations | $70.4M |
| Traffic Management | $66.8M | Electricity | $10.6M |
| Environmental Projects | $27.8M | Maintenance Support | $15.2M |
| Facilities, Equipment, Research | $52.6M | Other | $10.6M |
| Reimbursable Expenses, Other | $29.5M | | |
| **TOTAL*** | **$634.3M** | **TOTAL** | **$236.7M** |

*Total is accurate but does not equal the sum of sub-categories due to rounding.

***Figure A.7. SHA funding breakdown in FY2011.***

funding is programmed to carry out the project. Once planning and programming efforts have been conducted, the project then (typically) enters into the design phase. Following the final design acceptance, the project is then constructed or deployed, and acceptance testing is performed on the final deployment. Eventually, the deployed assets will be operated and maintained for a number of years until their life expectancy is met. As can be seen in Figure A.8, the overall CHART deployment process is cyclic. When the life expectancies of deployed assets are met, there comes a need for replacement assets to be deployed through a new project. The CHART Board of Directors also oversees the entire life cycle of each ITS project.

This is a brief description of the high-level steps within CHART's project planning and programming process.

1. This step in the CHART project planning and programming process involves gathering information from various inputs that are both internal and external to the CHART program. One of the CHART program's primary objectives is to coordinate with other offices/agencies/partners in order to effectively operate Maryland roadways. As such, CHART has an established place within several forums and processes that involve planning/interaction with other agencies (e.g., bordering/regional states, local and county agencies, other state modal transportation agencies, public safety agencies, emergency and medical operational agencies, among others), as well as other offices within the Maryland SHA. Like the CHART program, these partner agencies also have planning processes and documented initiatives, many of which identify resources that CHART will be responsible for deploying/providing. CHART's planning efforts, therefore, also need to account for various CHART resources allocated to support other agency initiatives.
2. Once projects are identified in the initial phase of the CHART planning and programming process, official documentation of these projects is initiated through the high-level summary process prior to being entered into the MDOT CTP.
3. The Maryland SHA and the Office of CHART, being part of MDOT, are responsible for contributing its portion of the six-year capital investment program within the CTP. As such, the Office of CHART's contribution to the MDOT CTP includes project titles and cost estimates to be programmed over the next six years. This includes budget

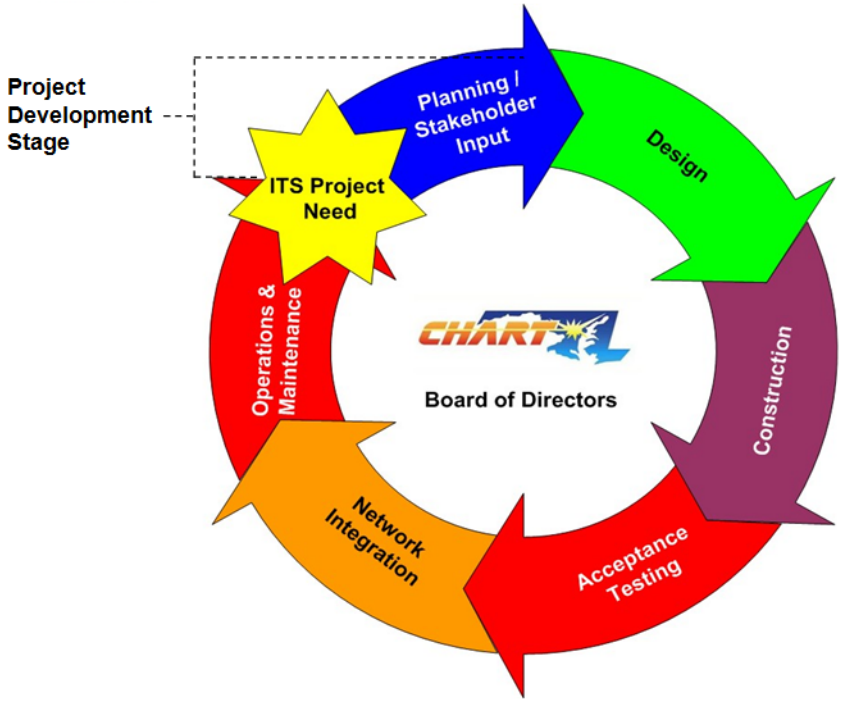



*Figure A.8. Overall CHART deployment process.*

projections for each project in yearly increments. CHART updates its projects and budgets every year for submittal to the MDOT CTP, showing the latest CHART capital investment six-year projection.

4. The CHART deployment plan presents and describes capital improvement projects that the Maryland SHA's Office of CHART is responsible for within the six-year MDOT CTP. Updated on an annual basis, the primary purpose behind the CHART deployment plan is to document detailed information on CHART projects to receive funding for the next six years through the CTP. As a result, the CHART deployment plan directly coincides with the CHART projects for the MDOT CTP document within the CHART project planning and programming process.
5. This step involves detailed project descriptions and ITS architectures and systems engineering (SE) analysis. This level of documentation takes place once projects are documented in the MDOT CTP and the CHART deployment plan. The detailed project description and ITS architecture/SE analysis phase is required to be carried out prior to a project going through the preliminary engineering phase (if applicable), and eventually entered into the Federal and MDOT project setup phase.
6. Once the needed project information is documented in the detailed project descriptions and/or SE analysis/project-level ITS architecture, the project can enter the preliminary design phase where all needed details about the deployment are gathered prior to beginning the final project design. It should be noted that not all Office of CHART projects require preliminary engineering services. An example could be a situation in which specific equipment will simply be procured through the project, and therefore engineering design services are not needed. In general, the most common types of projects that require preliminary engineering services are those in which ITS field devices are being deployed in new locations.
7. When preliminary engineering services are carried out and documented, the project needs to be set up in the Federal and/or MDOT project tracking systems, which track budget, payments, scheduling, and so forth. As discussed above, those projects that do not require project-level ITS architecture, SE analysis, or preliminary engineering services may be entered directly into the project setup phase.
8. Once the project is set up in the U.S.DOT/FHWA and/or MDOT project system, it can then move forward with design and deployment services. As such, the Office of CHART typically does not conduct design services for many of the projects it initiates through its planning process, and therefore, a design request is submitted by CHART to the Office of Traffic and Safety (OOTS) in order to officially move project design and construction management services to OOTS. This step also moves the

planning and programming process into project design and deployment.

## Other Example of a SHA Programming Process: Crash Prevention, Safety and Spot Improvement, and Intersection Capacity Improvement

Maryland has a number of additional internal project identification and programming processes, and following are three specific programs (Crash Prevention, Safety and Spot Improvement, and Intersection Capacity Improvement) that follow the same general process flow, but with differing criteria for rating candidate projects. It should be noted that while these projects could have travel time reliability impacts, reliability-based criteria or considerations are not included as part of the candidate project ratings. The current general process (which has been abbreviated) involves the following steps:

1. The SHA district offices identify a need, conduct a traffic study, and forward study to the Office of Traffic and Safety (OOTS).
2. If OOTS approves study, concept funding may be obtained through the Office of the Chief Engineer/Administrator to complete a concept development study (project impact report).
3. If OOTS approves the concept development study, a request is made for preliminary engineering funding through the Office of the Chief Engineer/Administrator.
4. Design is conducted; a plans, specifications, and estimates (PS&E) package is developed; and OOTS completes a benefit–cost analysis along with a completed rating and ranking form (criteria specific to each program is identified below).
5. Funding is requested through the Office of the Chief Engineer/Administrator and, if approved, is added to the CTP.
6. District moves forward with project and project is eventually constructed.

Following is a summary of rating criteria used in evaluating projects for selection under each program as mentioned in Step 4. These criteria are used as part of a candidate project rating form that determines an overall project rating based on weighted scores within associated weighted categories.

## Crash Prevention Program

Candidate projects are given a rating based on the categories of Safety (30%), Impacts (40%), Support/Difficulty (20%), and Congestion/Operations (10%). The percentages are the weights given to each category.

The Safety category criteria include

- Whether or not the improvement is on a list of previous Safety Improvement Candidate Locations
- Accident experience
- Police reported safety concern
- Conflicts observed/reported
- To what extent project improvement will address problem

The Impacts category criteria include

- Right-of-way and property
- Historical/archaeological
- Structures
- Environmental (wetlands, floodplains, critical areas)
- Utilities
- Storm water management and drainage
- Signals and lighting

The Support/Difficulty category criteria include

- Degree of support (from "Overwhelming Opposition" to "Overwhelming Support")
- Difficulty and associated cost (from "Difficult/Expensive [>$1M]" to "Easy/Cheap [<$500K]")

The Congestion/Operations category criterion includes

- Percent change in v/c ratio in AM and PM peak hours for existing and proposed conditions

## Safety and Spot Improvement Program

Candidate projects are given a rating based on the categories of Safety (60%), Congestion/Operations (30%), and Support/Opportunity (10%). The percentages are the weights given to each category.

The Safety category criteria include

- Relative position with regard to list of Safety Improvement Candidate Locations
- Accident experience
- To what extent project improvement will address problem

The Congestion/Operations category criteria include

- Need based on level of service (delay/capacity problems)
- To what extent project improvement will address problem

The Support/Opportunity criteria include

- Degree of support (from "Overwhelming Opposition" to "Overwhelming Support")

- Benefit/Cost/Difficulty (from “Expensive/Difficult” to “Cheap/Easy”)

## Safety and Spot Improvement Program

Candidate projects are given a rating based on the categories of Congestion/Operations (80%), Safety (10%), and Support/Opportunity (10%). The percentages are the weights give to each category.

The Congestion/Operations category criteria include the percentage change in the following measures of effectiveness in the AM and PM peak hours for existing conditions versus conditions after improvement:

- Intersection delay
- 95th percentile queue
- Level of service (*Highway Capacity Manual*)
- Volume to capacity (v/c) ratio

The Safety category criteria include

- Relative position with regard to High Accident Location (HAL) list
- Non-HAL accident experience
- To what extent project improvement will address problem

The Support/Opportunity criteria include

- Degree of support (from “Overwhelming Opposition” to “Overwhelming Support”)
- Difficulty/Cost (from “Very Difficult/$2.5–$4M” to “Easy/<$300K”)

APPENDIX B

# MATLAB Code

**GBM Calibration and Hypothesis Testing Function:**

```
function
[tt_mean,alpha,sigma,h]=gbm_calibrate(time,tt,period,corridor_name,segment_na
me,L,fig_handle,axis_handle)

if isempty(time)
    tt_mean=nan;
    alpha=nan;
    sigma=nan;
    h=nan;
    return
end
idx=isfinite(tt);
time=time(idx);
tt=tt(idx);

A=[time tt];
A=sortrows(A,1);
time=A(:,1);
tt=A(:,2);
tt_mean=nanmean(tt);
[~,~,D,H,MN,S]=datevec(diff(time));
dt=D.*1440+H.*60+MN+S./60;
sqrt_dt=sqrt(dt);
log_inst_interest=diff(log(tt));
sigma=nanstd(log_inst_interest)/nanmean(sqrt_dt);
alpha=nanmean(log_inst_interest)/nanmean(dt)+sigma^2/2;
```

```
%check for log-normal distribution
Y = log_inst_interest;
[h,p] = chi2gof(Y,'cdf',{@normcdf,alpha,sigma},'nparams',2);

if ~isempty(axis_handle)
    figure(fig_handle); subplot(axis_handle);
    histfit(Y,max(1,round(sqrt(size(Y,1)))),'normal');
    if h==0
        str1='CANNOT';
        str2='IS';
    else
        str1='CAN';
        str2='IS NOT';
    end
    title({
            ['ALPHA: ' num2str(alpha) '    SIGMA: ' num2str(sigma)];...
%             ['NULL HYPOTHESIS ' str1 ' BE REJECTED (@ 5% SIGNIFICANCE
LEVEL)'];...
            ['TRAVEL TIME ' str2 ' LOG-NORMALLY DISTRIBUTED']
            });
    xlabel('TRAVEL TIME LOGARITHM (LOG-MINUTE)');
    ylabel('FREQUENCY');
end
```

**Black-Scholes Option Valuation Function:**

```
function
X=BS(alpha,sigma,tau_initial,tau_guaranty,optlength,evaltime,tol,type)
% Black-Scholes formula
% Input:
%       alpha:          long-term trend (%)
%       sigma:          instantaneous variation (%)
%       tau_initial:    initial travel time
%       tau_guaranty:   guarnateed travel time
%       optlength:      option length (time)
%       evaltime:       time at which option is to be evaluated (time)
%       tol:            tolerance level (%)
%       type:           'call' or 'put' option
% Output:
%       X: option value

tleft=optlength-evaltime;
d1=(log(tau_initial/tau_guaranty)+(tol+.5*sigma^2)*tleft)/(sigma*sqrt(tleft))
;
d2=d1-sigma*sqrt(tleft);
if strcmpi(type,'CALL')
    X=tau_initial*normcdf(d1,0,1)-tau_guaranty*exp(-
tol*tleft)*normcdf(d2,0,1);
elseif strcmpi(type,'PUT')
    X=-tau_initial*normcdf(-d1,0,1)+tau_guaranty*exp(-tol*tleft)*normcdf(-
d2,0,1);
end

end
```

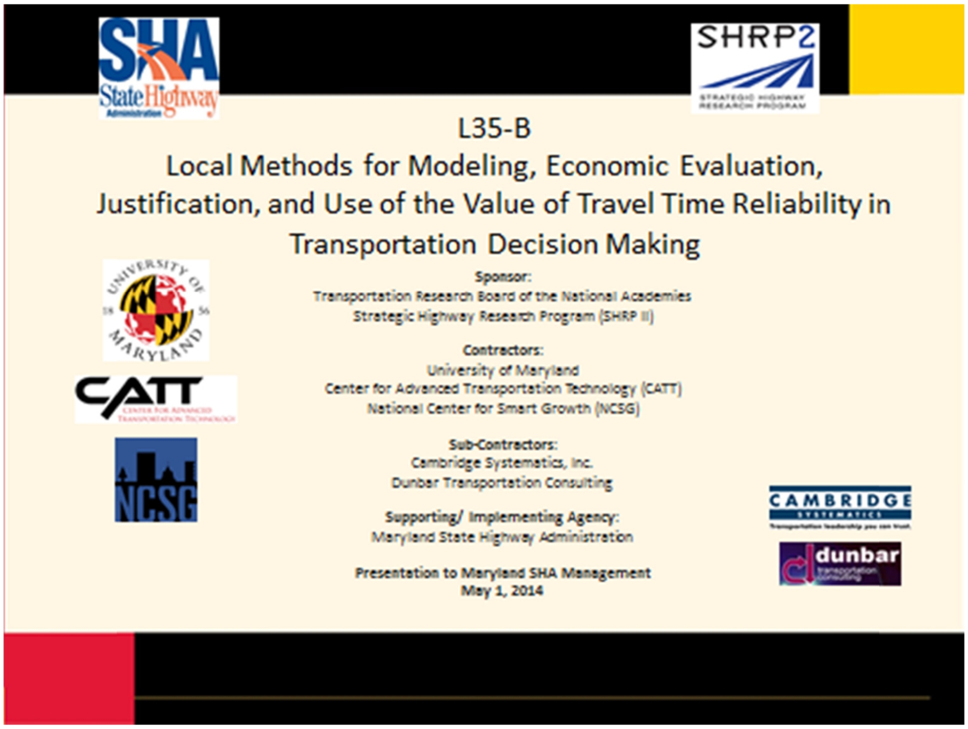
**Binary Tree Option Valuation Function:**

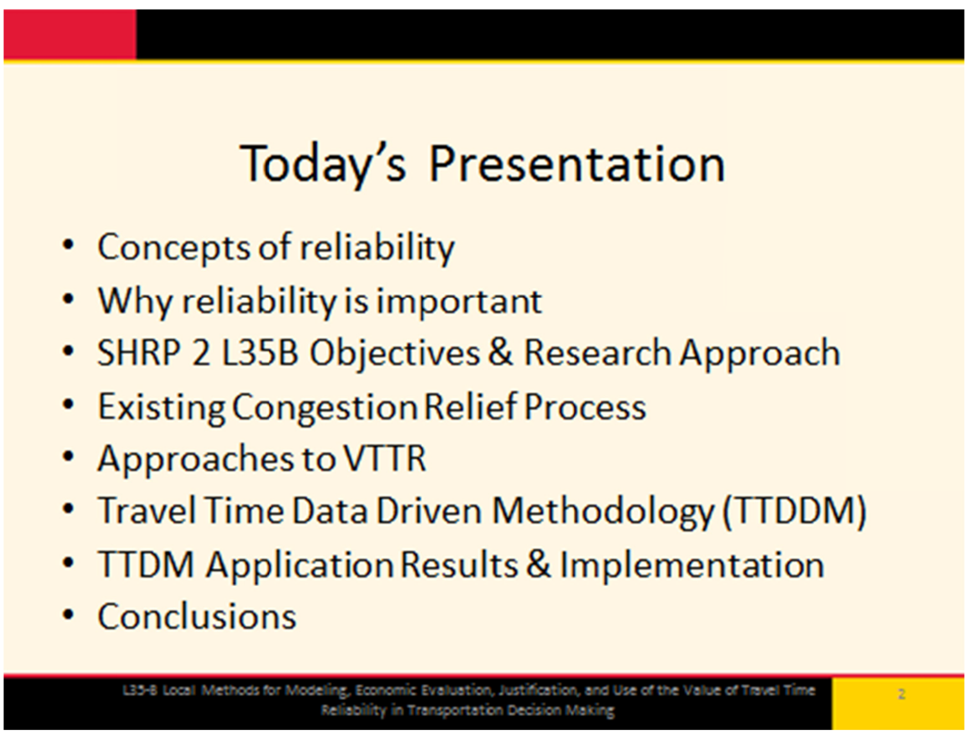
```
function
C=BinT(alpha,sigma,tau_initial,tau_guaranty,optlength,tol,n,late_penalty,earl
y_penalty)
% Binary Tree Option Valuation
% Input:
%       alpha:          long-term trend (%)
%       sigma:          instantaneous variation (%)
%       tau_initial:    initial travel time
%       tau_guaranty:   guarnateed travel time
%       optlength:      option length (time)
%       tol:            tolerance level (%)
%       n:              number of steps (whole number, positive)
%       late_penalty:   portion of VOT traveler will be penalized for
%                       arriving late (unitless)
%       early_penalty:  portion of VOT traveler will be penalized for
%                       arriving early (unitless)
% Output:
%       C: travel time option value

delta_t=optlength/n;
delta_h=sigma*sqrt(delta_t);
u=exp(delta_h);
d=exp(-delta_h);
q=.5*(1+(alpha/sigma-sigma/2)*sqrt(delta_t));
q_prime=1-q;
% risk neutral probability
p=(1-d+tol*delta_t)/(u-d);
p_prime=1-p;
% forward binary tree development
tree=nan(n+1,n+1);
tree(1,1)=tau_initial;
for i=1:n %time steps
    for j=1:i %travel time states
        tree(j,i+1)=tree(j,i)*u;
    end
    tree(j+1,i+1)=tree(j,i)*d;
end
% assigning binary probabilites to each node in the tree
prob=nan(n+1,n+1);
prob(1,1)=1;
for i=1:n
    prob(1:i+1,i+1)=binopdf(i:-1:0,i,p)';
end
% backward option valuation
option=nan(n+1,n+1);
option(:,n+1)=late_penalty*max(tree(:,n+1)-
tau_guaranty,0)+early_penalty*max(tau_guaranty-tree(:,n+1),0);
for i=1:n
    for j=1:n+1-i
        option(j,n+1-i)=(option(j,n+2-i)*p+option(j+1,n+2-
i)*p_prime)/(1+tol*delta_t);
    end
end
C=option(1,1);
% plot(tree(:,end),prob(:,end)); hold all;
% xlim([0 1000]);
% ylim([0 1]);
end
```

APPENDIX C

# Presentation to Maryland State Highway Administration

## L35B Local Methods for Modeling, Economic Evaluation, Justification, and Use of the Value of Travel Time Reliability in Transportation Decision Making



## Concepts of Reliability

- Don't arrive late
- Certainty of travel time
- Don't arrive early
  - Early preferable to late
- Does not mean free flow
- Types of reliability
  - Link
  - Path
  - Point to point
- Value of Travel Time Reliability
  - Reliability Ratio (RR) = Value of Reliability (VOR) / Value of Time (VOT)



## Importance of Reliability

- Person
  - Late – lost opportunity, wages
  - Early – time wasted
- Firm
  - Late – extra wages
  - Early – workforce idle time
  - Just in time delivery – potential large impact
- To SHA
  - Understand full benefit of improvements
  - Lack of reliability can be source of complaints

## L35B Project Objectives

- "Select and defend a value or range of values for travel time reliability for the Maryland State Highway Network";
- "Use the VTTR in the Maryland SHA project development process to prioritize operational and capital improvements and determine if (and how) the ranking of projects changes due to the addition of VTTR"; and
- "Report for the benefit of others the step-by step process used to develop, justify, apply, and assess the use of VTTR in the Maryland SHA project evaluation and decision process."

L35-B Local Methods for Modeling, Economic Evaluation, Justification, and Use of the Value of Travel Time Reliability in Transportation Decision Making

5

## Research Approach

- Documented established processes
- Conducted detailed literature search
- Developed travel time data driven methodology
- Acquired data needed
- Applied TTDDM to multiple corridors to calculate RR/VOR
- Incorporated RR/VOR results in short term and long term project selection processes

L35-B Local Methods for Modeling, Economic Evaluation, Justification, and Use of the Value of Travel Time Reliability in Transportation Decision Making

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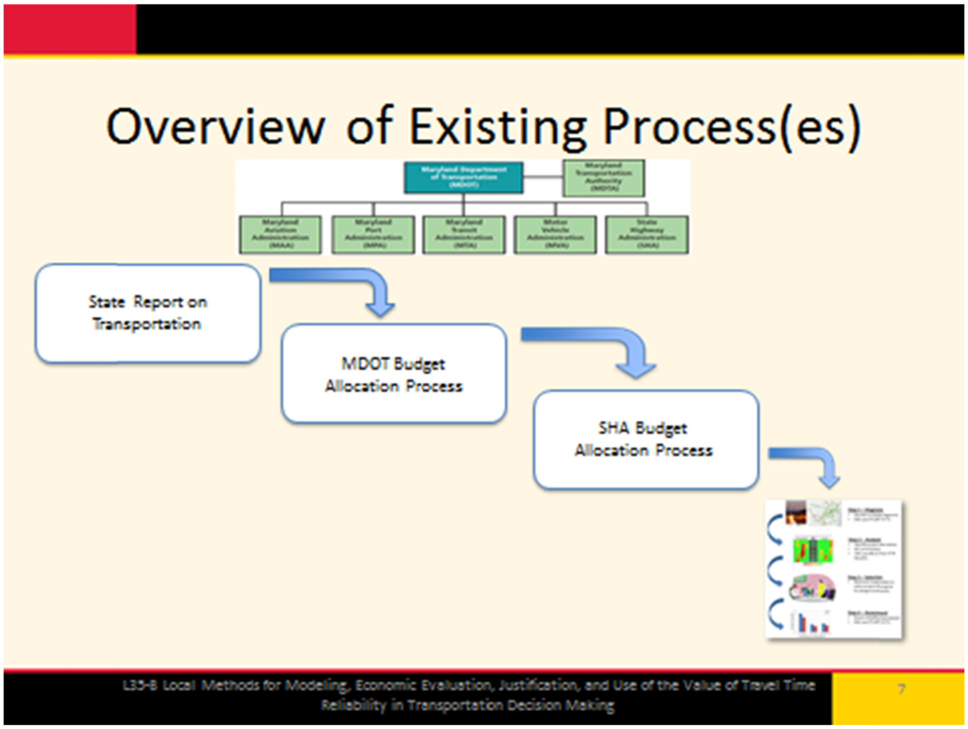
Overview of Existing Process(es)
State Report on Transportation
MDOT Budget Allocation Process
SHA Budget Allocation Process
L35-B Local Methods for Modeling, Economic Evaluation, Justification, and Use of the Value of Travel Time Reliability in Transportation Decision Making
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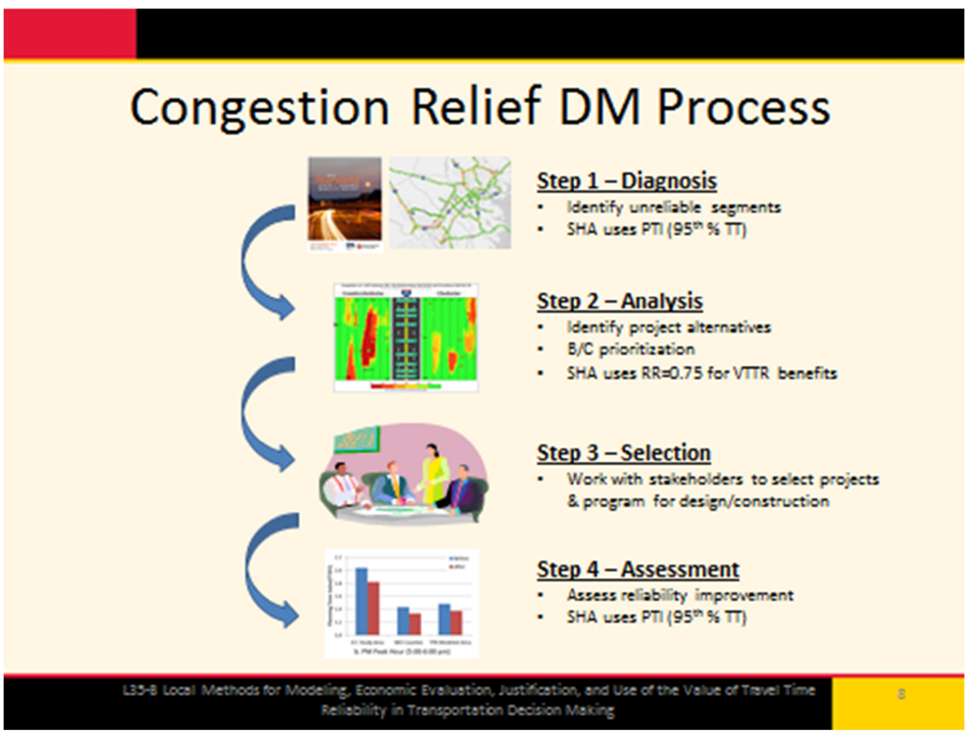
Congestion Relief DM Process
Step 1 – Diagnosis
• Identify unreliable segments
• SHA uses PTI (95th % TT)
Step 2 – Analysis
• Identify project alternatives
• B/C prioritization
• SHA uses RR=0.75 for VTTR benefits
Step 3 – Selection
• Work with stakeholders to select projects & program for design/construction
Step 4 – Assessment
• Assess reliability improvement
• SHA uses PTI (95th % TT)
L35-B Local Methods for Modeling, Economic Evaluation, Justification, and Use of the Value of Travel Time Reliability in Transportation Decision Making
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# Congestion Relief Project DM

- Some Step 2 Analysis Details
  - Benefits: VOT and VTTR

Value of Time (VOT)

- Passenger: U.S. Census Bureau data
- Truck driver: Bureau of Labor Statistics, US DOT, and FHWA's HERS
- Cargo: TTI, and other studies

Value of Travel Time Reliability (VTTR)

- Reliability Ratio (RR=0.75)
- Based on literature review and current practice in other parts of the world

| Saving Type | Parameter | Unit | Categories | SHA Value* |
|---|---|---|---|---|
| Travel time | VOT | $/hr | Passenger | 29.82 |
| | | | Truck driver | 20.21 |
| | | | Cargo | 45.40 |
| Travel time reliability | VTTR | $/hr | Passenger | 22.36 |
| | | | Truck driver | 15.16 |
| | | | Cargo | 34.05 |
| Fuel cost | | $/gal | Gasoline | 3.69 |
| | | | Diesel | 3.97 |

*Parameters used by SHA in project benefit estimation (2012 values)

L35-B Local Methods for Modeling, Economic Evaluation, Justification, and Use of the Value of Travel Time Reliability in Transportation Decision Making

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# Previous Approaches to Estimate VTTR

- **Statistical methods (early studies)**
  - Directly estimate TT distribution and variations
    - Mean-variance
    - Scheduling delay
    - Combined mean-variance and scheduling delay
- **Survey-based methods (later)**
  - Discrete choice models
    - Disaggregate survey data, stated preferences (SP) or revealed preferences (RP) or combination
- **Options Theory (emerging)**
  - Unique approach based on statistical/financial concepts
  - Uses an analogy where premiums are set for an insurance policy that guards against being late
  - Data driven
    - uses historical travel time, speed and volume data as input readily available to most agencies
  - Easy to update, generalize and localize

L35-B Local Methods for Modeling, Economic Evaluation, Justification, and Use of the Value of Travel Time Reliability in Transportation Decision Making

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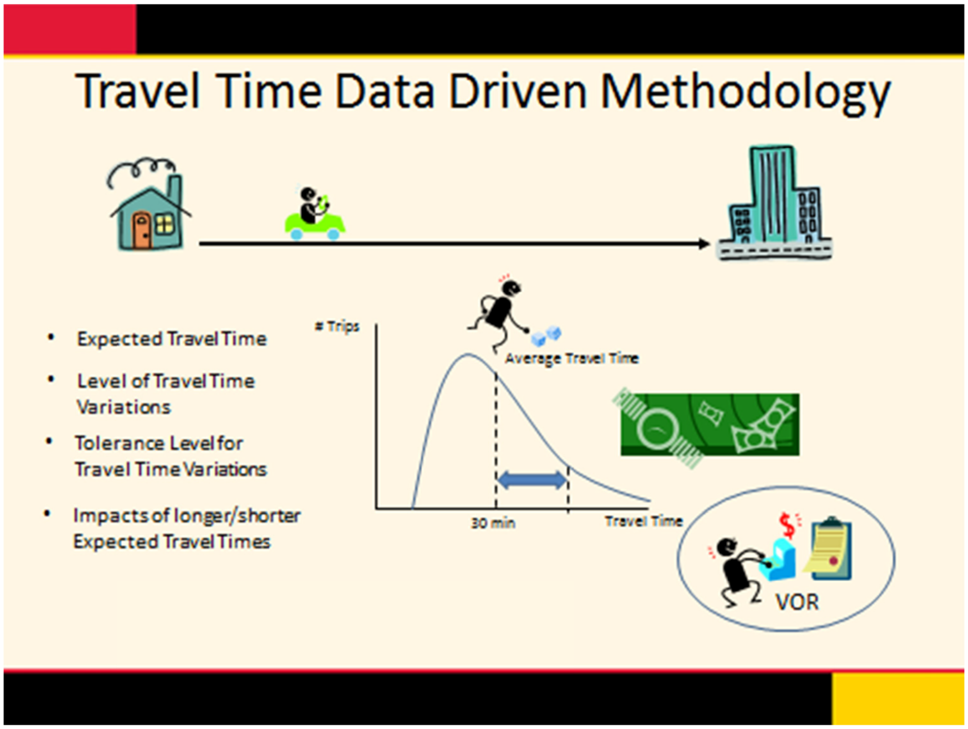
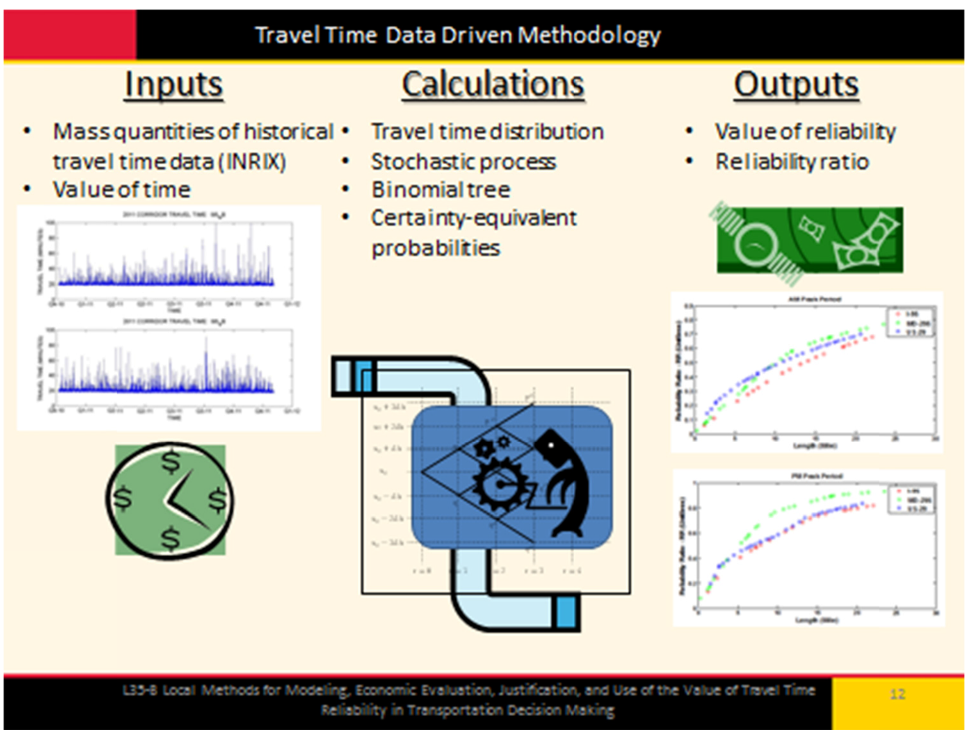

Travel Time Data Driven Methodology
Expected Travel Time
Level of Travel Time Variations
Tolerance Level for Travel Time Variations
Impacts of longer/shorter Expected Travel Times
# Trips
Average Travel Time
30 min
Travel Time
VOR


Travel Time Data Driven Methodology
Inputs
Mass quantities of historical travel time data (INRIX)
Value of time
Calculations
Travel time distribution
Stochastic process
Binomial tree
Certainty-equivalent probabilities
Outputs
Value of reliability
Reliability ratio
L35-B Local Methods for Modeling, Economic Evaluation, Justification, and Use of the Value of Travel Time Reliability in Transportation Decision Making
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# Corridors Analyzed

L35-B Local Methods for Modeling, Economic Evaluation, Justification, and Use of the Value of Travel Time Reliability in Transportation Decision Making

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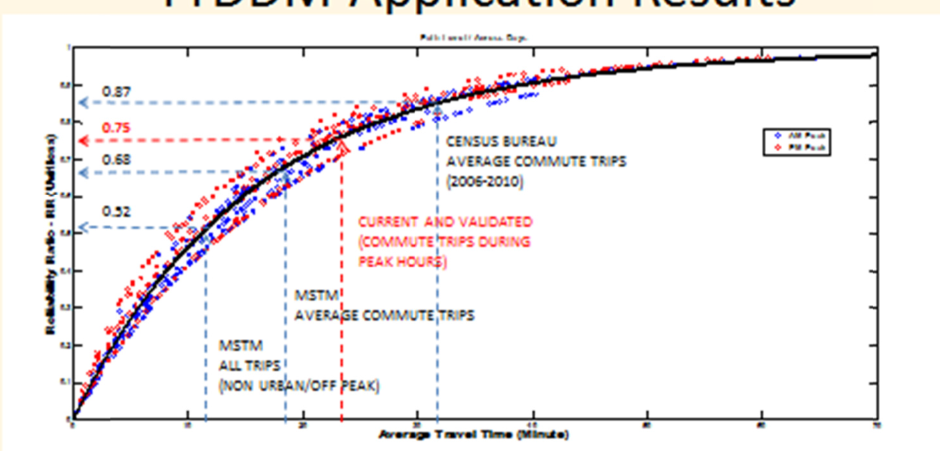
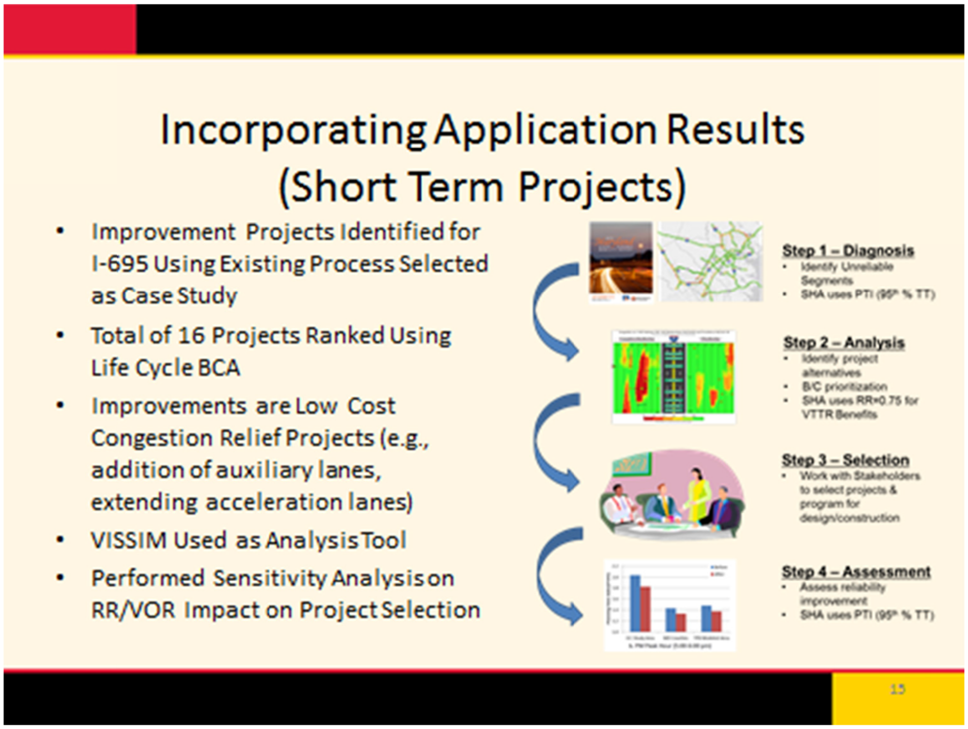
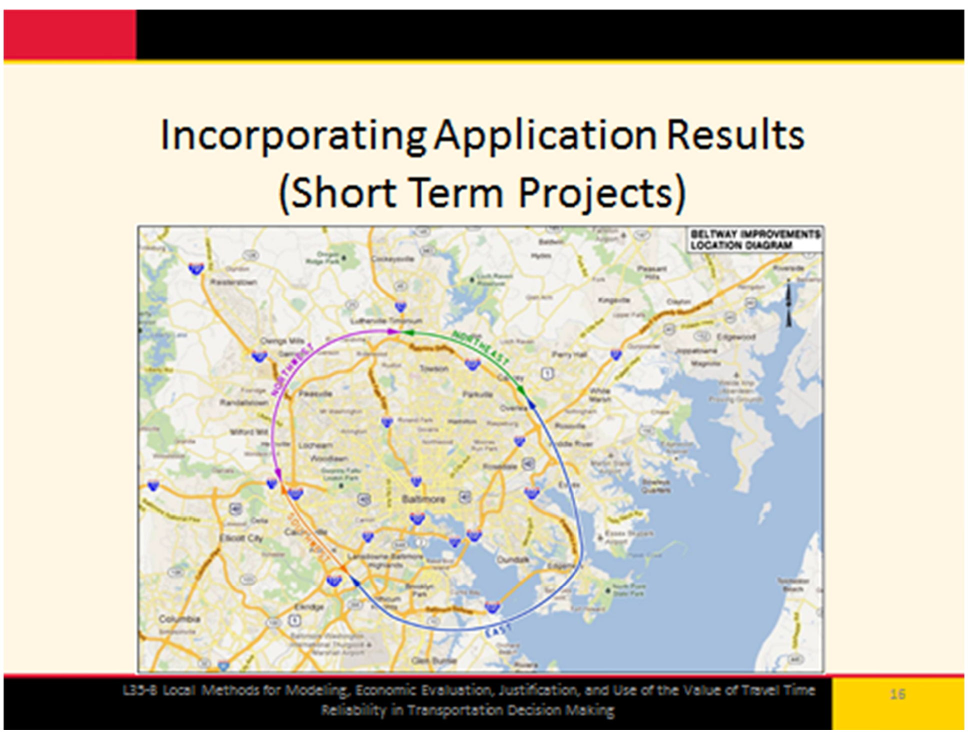
# TTDDM Application Results




Incorporating Application Results
(Short Term Projects)
• Improvement Projects Identified for I-695 Using Existing Process Selected as Case Study
• Total of 16 Projects Ranked Using Life Cycle BCA
• Improvements are Low Cost Congestion Relief Projects (e.g., addition of auxiliary lanes, extending acceleration lanes)
• VISSIM Used as Analysis Tool
• Performed Sensitivity Analysis on RR/VOR Impact on Project Selection
Step 1 – Diagnosis
• Identify Unreliable Segments
• SHA uses PTI (95th % TT)
Step 2 – Analysis
• Identify project alternatives
• B/C prioritization
• SHA uses RR=0.75 for VTTR Benefits
Step 3 – Selection
• Work with Stakeholders to select projects & program for design/construction
Step 4 – Assessment
• Assess reliability improvement
• SHA uses PTI (95th % TT)
15


Incorporating Application Results
(Short Term Projects)
BELTWAY IMPROVEMENTS LOCATION DIAGRAM
NORTHWEST
NORTHEAST
SOUTHWEST
EAST
Baltimore
L35-B Local Methods for Modeling, Economic Evaluation, Justification, and Use of the Value of Travel Time Reliability in Transportation Decision Making
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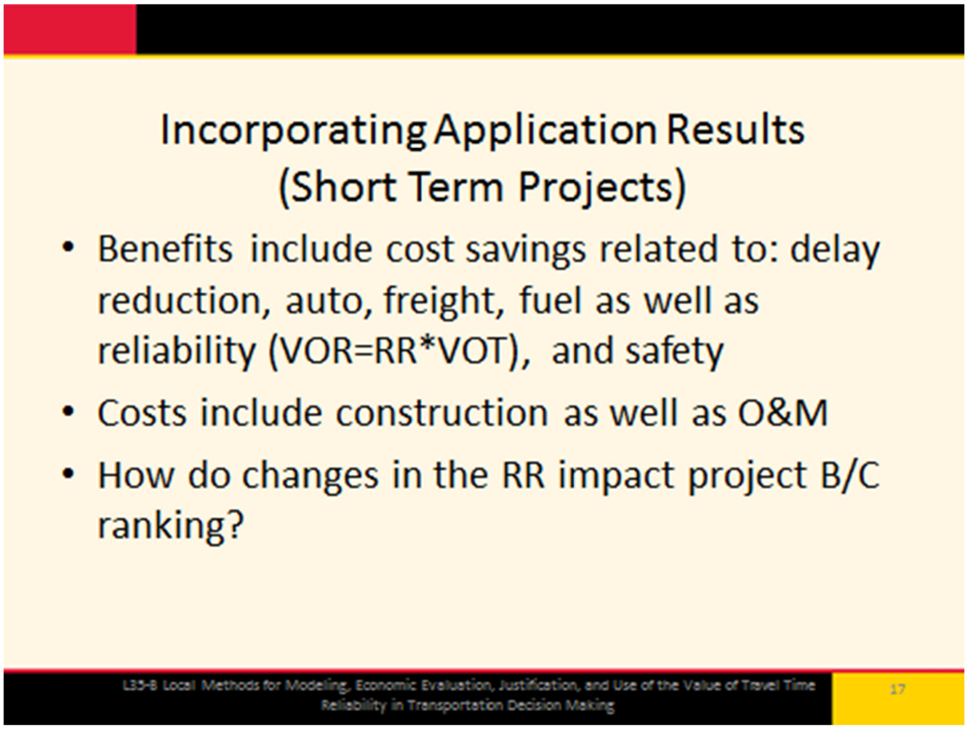
Incorporating Application Results
(Short Term Projects)
• Benefits include cost savings related to: delay reduction, auto, freight, fuel as well as reliability (VOR=RR*VOT), and safety
• Costs include construction as well as O&M
• How do changes in the RR impact project B/C ranking?
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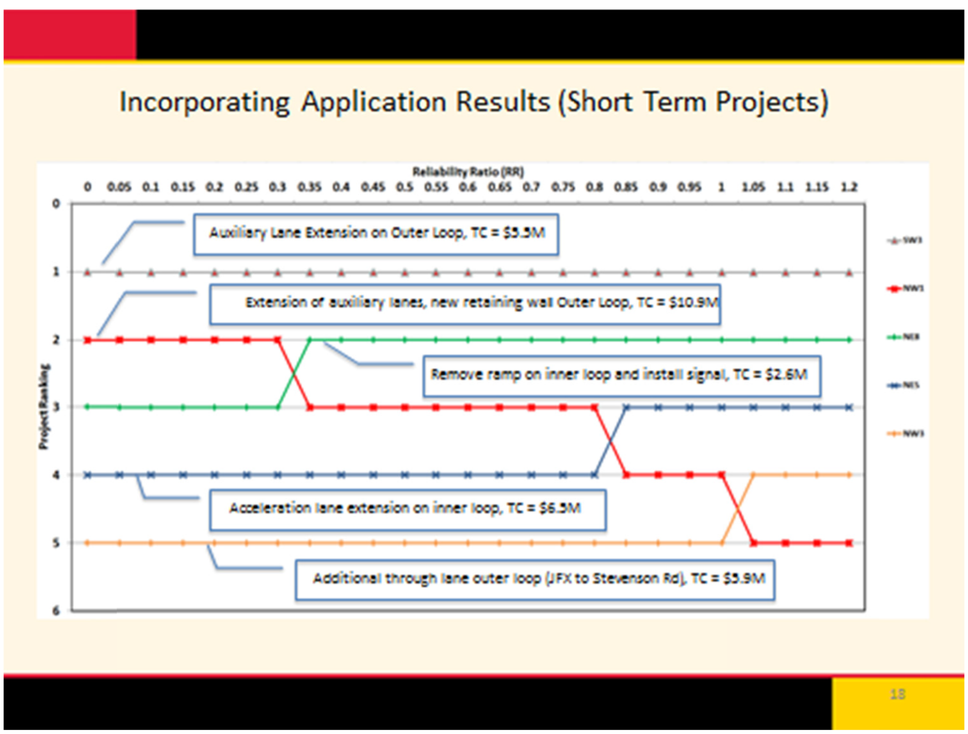
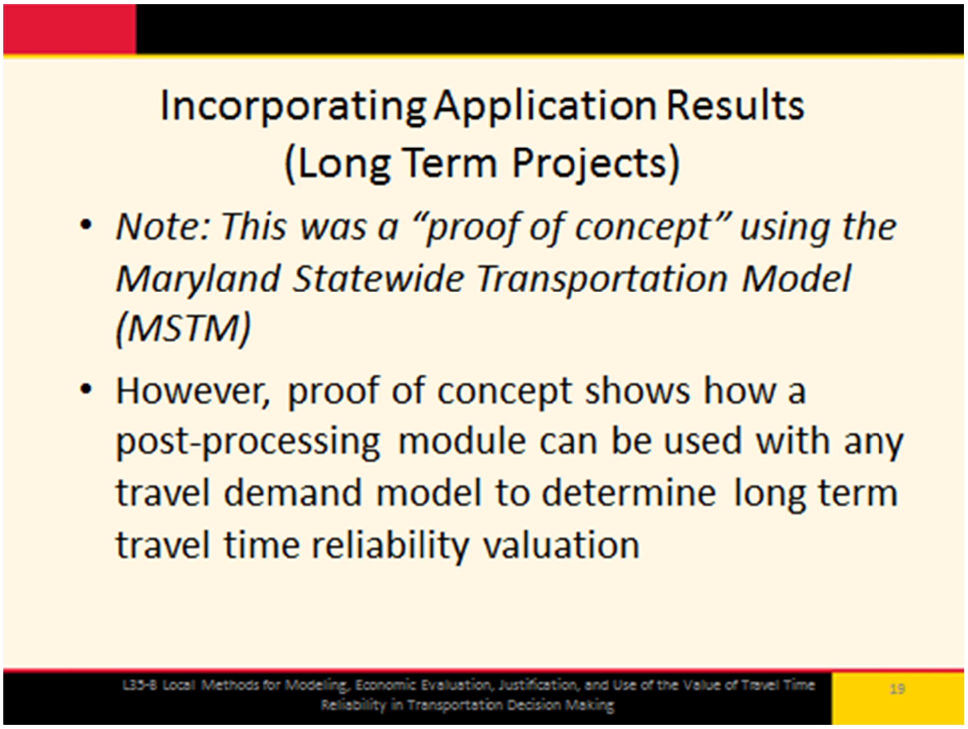

Incorporating Application Results (Short Term Projects)
Reliability Ratio (RR)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1 1.05 1.1 1.15 1.2
Project Ranking
0 1 2 3 4 5 6
Auxiliary Lane Extension on Outer Loop, TC = $5.5M
Extension of auxiliary lanes, new retaining wall Outer Loop, TC = $10.9M
Remove ramp on inner loop and install signal, TC = $2.6M
Acceleration lane extension on inner loop, TC = $6.5M
Additional through lane outer loop (JFX to Stevenson Rd), TC = $5.9M
SW3
NW1
NE8
NE5
NW3
18


Incorporating Application Results
(Long Term Projects)
• Note: This was a "proof of concept" using the Maryland Statewide Transportation Model (MSTM)
• However, proof of concept shows how a post-processing module can be used with any travel demand model to determine long term travel time reliability valuation
L35-B Local Methods for Modeling, Economic Evaluation, Justification, and Use of the Value of Travel Time Reliability in Transportation Decision Making
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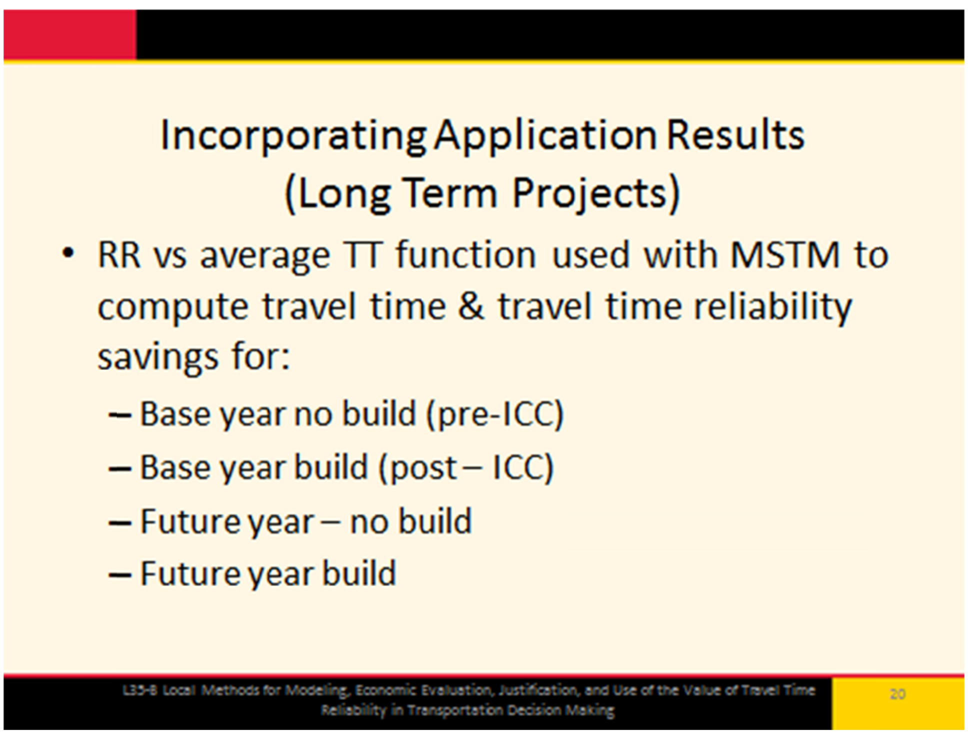
Incorporating Application Results
(Long Term Projects)
• RR vs average TT function used with MSTM to compute travel time & travel time reliability savings for:
– Base year no build (pre-ICC)
– Base year build (post – ICC)
– Future year – no build
– Future year build
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# State Level Findings

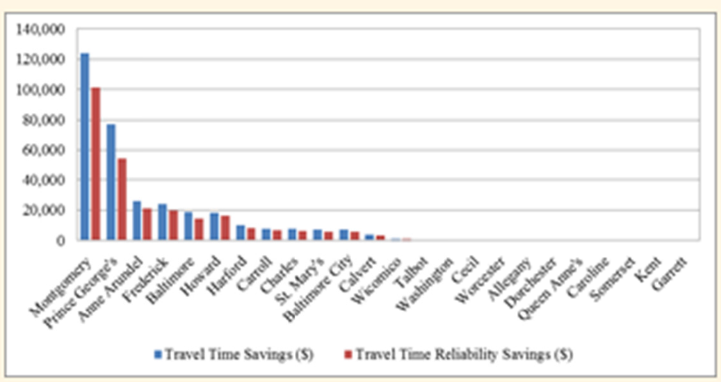
- AM and PM peak periods, base year post-ICC vs. pre-ICC and future year build vs. future year no build (savings over 1 year)

| Year | Total Savings | Travel Time (Minutes) | Travel Time ($) |
|---|---|---|---|
| Base Year | Travel Time | 449,915,060 | 104,965,240 |
| | Travel Time Reliability | 416,446,020 | 97,157,160 |
| | | **Total Base Year** | 202,122,400 |
| Future Year | Travel Time | 1,812,587,810 | 422,876,590 |
| | Travel Time Reliability | 1,837,341,380 | 428,651,620 |
| | | **Total Future Year** | 851,528,210 |



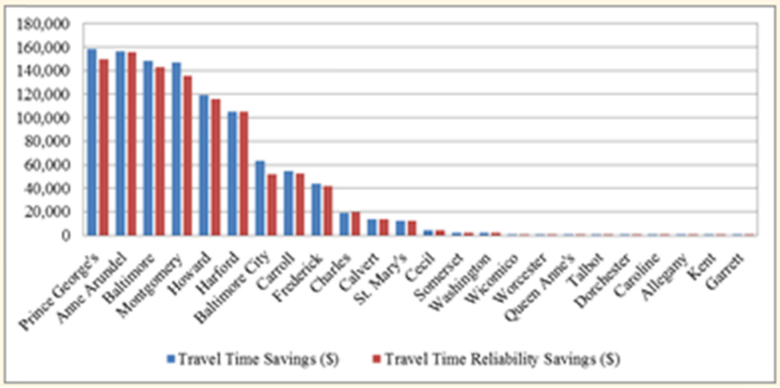
# County Level Findings

- Typical day, AM peak period, base year post-ICC vs. pre ICC



# County Level Findings

- Typical day, AM peak period, future year build

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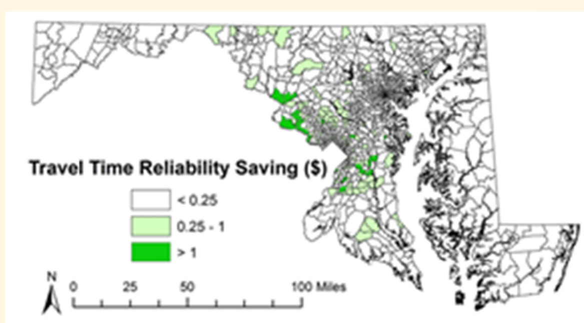
# TAZ Level Findings

- Travel time reliability savings $/trip post-ICC vs. pre-ICC

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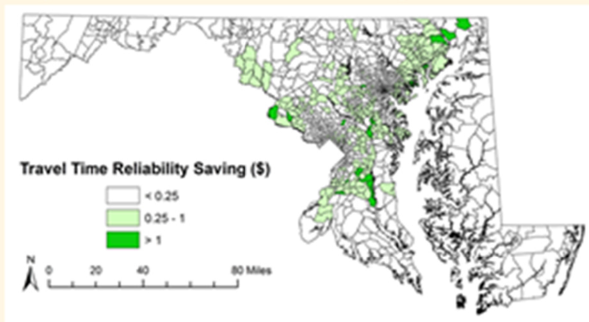
# TAZ Level Findings

- Travel time reliability savings $/trip post-future year build vs. future year no build

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# Corridor Level Findings

- I-270 AM Peak Period, NB & SB, Post ICC vs Pre ICC and Future Year Build vs No Build

| Scenario | I-270 Travel Time (Min) | | I-270 RR | | I-270 TT Savings(min)/ Traveler | | I-270 TTR Savings(min) / Traveler | |
|---|---|---|---|---|---|---|---|---|
| | NB | SB | NB | SB | NB | SB | NB | SB |
| Base-No Build | 20.2 | 23.8 | 0.74 | 0.79 | 1.6 | 2.0 | 1.7 | 2.2 |
| Base-Build | 18.6 | 21.8 | 0.71 | 0.77 | | | | |
| Future-No Build | 21.6 | 25.7 | 0.76 | 0.82 | 1.8 | 2.0 | 1.9 | 2.2 |
| Future-Build | 19.8 | 23.7 | 0.73 | 0.79 | | | | |

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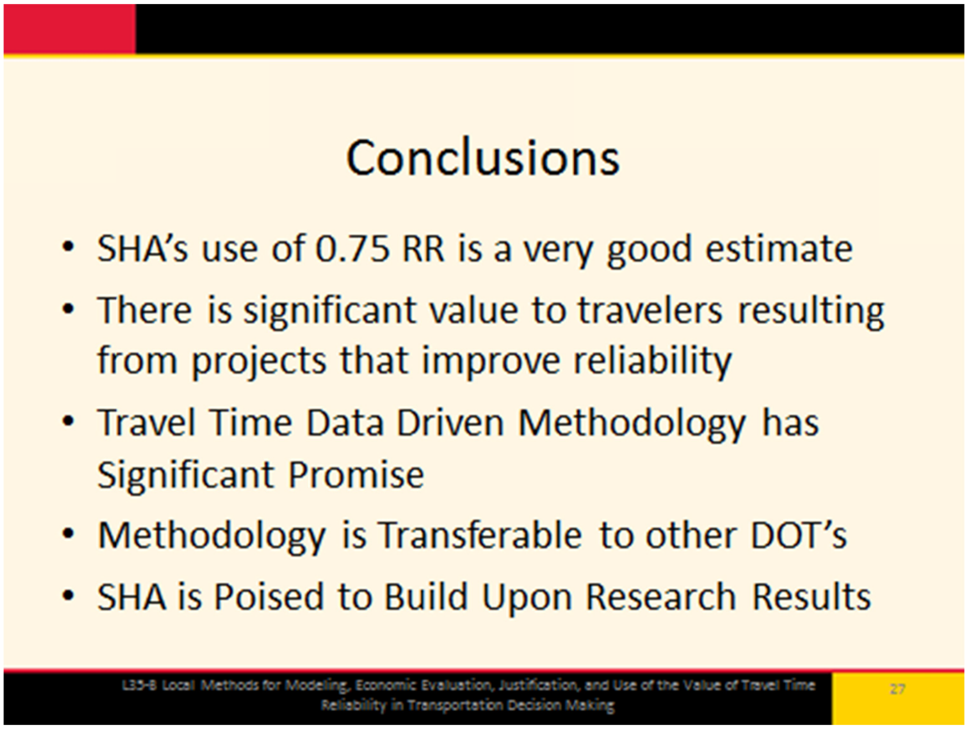
Conclusions
• SHA's use of 0.75 RR is a very good estimate
• There is significant value to travelers resulting from projects that improve reliability
• Travel Time Data Driven Methodology has Significant Promise
• Methodology is Transferable to other DOT's
• SHA is Poised to Build Upon Research Results
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PART 2

# DESCRIPTION OF THE METHOD

While the data-driven method shows promise, additional validation is required for the underlying theories, method, and test applicant results. Suggestions for further research are presented in this section.

CHAPTER 5

# Introduction

The objectives of the L35B project are to

- Select and defend a value or range of values for travel time reliability for the Maryland State Highway network.
- Use the value of travel time reliability (VOR) in the Maryland State Highway Administration (SHA) project development process to prioritize operational and capital improvements and determine if (and how) the ranking of projects changes due to the addition of VOR.
- Report for the benefit of others the step-by-step process used to develop, justify, apply, and assess the use of VOR in the Maryland SHA project evaluation and decision process.

This technical memorandum is the deliverable for L35B Task 2, which was to develop and apply a methodology to select a travel time reliability performance measure and a value or range of values for travel time reliability.

Currently, the Maryland SHA is using planning time index (PTI) to measure travel time reliability on highway facilities. Also, the Maryland SHA has adopted a 0.75 reliability ratio (RR) to measure the economic benefits of improvements in travel time reliability when conducting benefit–cost analysis of congestion relief projects. Conventionally, RR is defined as the ratio of value of travel time reliability (VOR) and value of time (VOT). This value is adopted by the Maryland SHA based on a comprehensive literature search of existing national and international resources as well as existing federal recommendations for RR value. This task report seeks to validate this number or provide a basis for changing it based on local data.

A data-driven methodology is proposed for estimating a reliability ratio (RR) and ultimately a value of travel time reliability (VOR). The methodology has been implemented in MATLAB to automate the process. A year's worth of archived probe-based travel time data is used to estimate the local RR and VOR values on five different corridors (in two directions) in Maryland. The initial results indicate that the current number is conservative and may have to be revised. However, the estimated number (0.87) is believed to be at the upper range of values for travel time reliability. Further analysis is needed to justify any decision to increase the current value of travel time reliability. This analysis will be facilitated by some of the data that are currently being used to complete tasks 3, 4, and 5 of this project. In particular, Maryland Statewide Transportation Model (MSTM) results will be crucial in aggregating the results for all origin–destination (O-D) pairs in the state. It is recommended, at this point, to consider 0.75 to 0.87 as the local range of viable values for the travel time reliability ratio.

This report includes specific details of an approach to estimate VOR and RR. The proposed method is data driven and requires access to fine granularity and long-term archived travel time data. This method is based on the analogy of an insurance policy designed to cover travelers against the negative impacts of unexpected variations in travel time. The proposed method has been designed to provide maximum flexibility for valuing travel time reliability based on existing local information and experiences. A review of the previous attempts to apply Real Options concepts to the problem of travel time reliability valuation is provided. Reasons as to why the previous attempts have received a cautious review are explained. Also, this report sets out to unravel some of the less clear parts of previous works by venturing further into the nuts and bolts of the approach. This report clearly identifies the distinctions between the proposed method and the earlier works.

Also, included in the report is a brief background on classical utility theory and its application in travel time reliability valuation. Strengths and limitations of utility-based estimation methods are discussed. A travel time insurance analogy is adopted to illustrate different aspects of the proposed approach. Setting a premium on the proposed travel time insurance is presented and discussed in the context of option-theoretic valuation and asset pricing. Examples are provided throughout the text to facilitate the discussions and to demonstrate application of the concepts. Applications of the proposed methodology using a year's worth of travel time data in the state of Maryland are reported. Analysis performed on the results of this application are presented and models to relate the travel time reliability ratio and average travel time, as well as 95th percentile travel time and average travel time, are calibrated. The next steps to finalize the range of values for travel time reliability in the state, based on the statewide model's results, are discussed.

Finally, this technical memorandum includes two appendices. Appendix D provides a brief review of stochastic processes, and in particular, the geometric Brownian motion process, including its properties and relationships with random walks. Appendix E presents more details about the application of the proposed methodology to the 10 directional corridor cases in Maryland and their various results.

## Real Options and Applicability to Travel Time Reliability Valuation

In this section an analogy is used to develop a methodology to select a value or range of values for travel time reliability. The analogy relates to an insurance premium that one would be willing to pay in order to keep one's travel time below a certain threshold. For instance, if a traveler, based on experience, knows that their morning commute to work takes 10 minutes on average, they might be willing to add 5 minutes to their trip time so that they could be certain the trip time would be less than 15 minutes; otherwise they will be compensated for any additional time spent on the trip. In other words, this approach strives to find a certainty equivalent for travel time unreliability in terms of additional expected travel time.

From this brief description it is clear that this valuation approach relies on knowledge of the following factors from a traveler's perspective:

- Expected travel time;
- Level of travel time variations;
- Acceptable level of travel time variations (traveler's tolerance); and
- A sense of how longer than expected travel times (or even shorter) will negatively (or maybe sometimes even positively) affect the traveler's experience.

In addition, from a rational decision making perspective, the valuation approach should take into account conditions under which the traveler would consider existing travel time variations as reliable. These certainty-equivalent conditions would, in fact, determine the state of the world in which a traveler would be indifferent between experiencing an unreliable travel time scenario or incurring an additional (but fixed) travel time up front that guarantees a certain level of travel time reliability.

The approach stems from asset pricing efforts in finance in which risky assets are valued according to their expected future payoffs. The specific type of assets that is commonly used to model insurance policies are referred to as options. Options are common in stock trading and are meant to protect shareholders against excessive increase or decrease in share prices.

CHAPTER 6

# Background

Before details of the proposed approach are presented, some background is provided on the relationship between travel time and travel cost, the role of random utility in classic discrete choice analysis, and definitions of travel time and travel time reliability values based on the existence of a utility concept. In addition, two different approaches to travel time reliability valuation based on the travel time insurance analogy are presented. These approaches include the Real Options concept and option pricing theory in the context of general consumption-based asset pricing. Applications of Real Options in the field of transportation decision making, planning, and reliability valuation are also briefly reviewed.

## Travel Time and Cost

Travel time and travel cost are usually directly linked to each other. It is common practice to assume travel cost (TC) is equal to travel time (TT) times a constant factor. This factor is commonly referred to as value of time (VOT), which reflects the perceived rate at which travelers would value the time they spend in their trips. The linear relationship between travel time and travel cost is shown in Equation 6.1.

$$TC = TT \times VOT \tag{6.1}$$

It should be noted that this is the simplest expression of travel cost as a function of travel time. If a more general form is known to exist that better specifies this relationship (such as multivalued, piecewise, or nonlinear functions), the proposed methodology, in its general form, will be capable of estimating appropriate travel time reliability values.

## Discrete Choice Analysis and Random Utility/Consumer Theory

Discrete choice analysis, in the context of trip decisions, is based on consumer theory in microeconomics. Consumer theory allows for modeling the action of consumers under given circumstances (e.g., budget, prices). A discrete choice model can be presented by a set of general assumptions about (*1*)

1. Decision maker (individual, household, socioeconomic attributes)
2. Alternatives (set of options available to the decision maker)
3. Attributes (the measures of benefit/cost of an alternative available to the decision maker)
4. Decision rule (the process by which the decision maker chooses an alternative)

The decision rule commonly used for travel behavior applications is based on utility theory, which assumes a decision maker's preference for an alternative is captured by utility, a single value that is a function of decision maker and alternatives attributes. The decision maker selects the alternative with the highest utility. Random utility theory assumes that the decision maker has perfect discrimination capability but, at the same time, the utility cannot be exactly specified. In fact, the uncertainty in utility may be explained by (*2*)

- Unobserved alternative attributes;
- Unobserved individual characteristics (taste variations);
- Measurement errors; and
- Proxy, or instrumental variables.

## Classic VOT and VOR Estimation

Value of travel time reliability (VOR) is usually derived from utility function calibration performed in the context of discrete choice analysis for travel demand modeling. This approach is basically known as a risk-return model in finance, in which a decision maker looks to maximize the asset's return while minimizing its associated risk. The asset's return is represented by the expected value and the risk by the variance (*3*). In the current context, therefore, both expected travel time and its variability (a measure of unreliability) are regarded as sources of disutility.

In its most general form, the deterministic part of the utility of an alternative (mode, route, or both) can be stated as a function of expected travel time (TT), associated out-of-pocket cost (OPC) of travel, and some measure of travel time (un) reliability/variation (RM) as shown in Equation 6.2.

$$u = U(\text{TT}, \text{OPC}, \text{RM}) + \varepsilon \tag{6.2}$$

In the classic approach, VOT is specified as a ratio of the marginal utility with respect to travel time and the marginal utility with respect to out-of-pocket cost. In essence, based on this definition VOT is the rate of substitution between the marginal utility of average travel time and the marginal utility of the trip's out-of-pocket cost (*10*) as shown in Equation 6.3.

$$\text{VOT} = \frac{\partial U/\partial \text{TT}}{\partial U/\partial \text{OPC}} \tag{6.3}$$

VOT is known to vary with trip purpose, income level, and other socioeconomic attributes of the subject population. Practical evidence shows that the magnitude of VOT estimated based on this approach is normally comparable to the relevant wage rate of the individual decision maker or the subject population.

Similarly, VOR may be estimated in an identical manner to VOT from a utility function calibration. VOR is the rate of substitution between the marginal utility of travel time unreliability and the marginal utility of the trip's out-of-pocket cost as shown in Equation 6.4.

$$\text{VOR} = \frac{\partial U/\partial \text{RM}}{\partial U/\partial \text{OPC}} \tag{6.4}$$

However, apart from the practical difficulties in conducting regular preference surveys (stated or revealed), other theoretical obstacles still exist that render applying this approach difficult to implement if not impractical in most cases. First, the fact that average travel time and travel time variability measures are naturally correlated makes it difficult to find unbiased VOT and VOR estimates using this approach. Second, stated preference respondents are known to have a subjective bias toward shorter average travel times and alternatives with lower costs. Nevertheless, random utility-based models are state-of-the-practice in estimating the above measures.

Reliability ratio (RR) is classically defined as the ratio of value of reliability (VOR) to the value of time (VOT). In other words, reliability ratio is the fraction of VOT that specifies the value travelers assign to a unit variation in their travel time as shown in Equation 6.5.

$$\text{RR} = \frac{\text{VOR}}{\text{VOT}} = \frac{\partial U/\partial \text{RM}}{\partial U/\partial \text{TT}} \tag{6.5}$$

It should be noted that the RR definition in Equation 6.5 is based again d on the rate of substitution between two relevant marginal utilities. Note that in the special (and widely used) case where utility can be expressed as an additive linear function, VOT, VOR, and RR will be equal to the ratios of the relevant parameters in the utility function. Equations 6.6 through 6.9 follow.

$$U = a \times \text{TT} + b \times \text{OPC} + c \times \text{RM} + \varepsilon \tag{6.6}$$

$$\text{VOT} = a/b \tag{6.7}$$

$$\text{VOR} = c/b \tag{6.8}$$

$$\text{RR} = c/a \tag{6.9}$$

## Utility-Based Reliability Valuation

To estimate a value for travel time reliability, a simple approach based on the concept of utility in discrete choice analysis is presented. For a given individual and a given trip, substitution between different attributes while utility is maintained at a constant level (indifferent decision maker) can be used to estimate a reliability value. To explain this approach further, let's assume that a certainty-equivalent addition to the average travel time ($X$) is known; the utility function in Equation 6.6 can be written as shown in Equation 6.10.

$$u = U(\text{TT} + X, \text{OPC}, \text{RM}_r) \tag{6.10}$$

where ($\text{RM}_r$) is a known parameter referring to the level of travel time variability measure that is perceived as tolerable by decision makers. Using the first-order Taylor's expansion around the current point (TT, OPC, RM), Equation 6.10 can be approximated by the expression shown in Equation 6.11:

$$u \cong U(\text{TT}, \text{OPC}, \text{RM}) + (\partial U/\partial \text{TT})X + (\partial U/\partial \text{RM})(\text{RM}_r - \text{RM}) \tag{6.11}$$

Comparing Equations 6.2 and 6.10, it is clear that to maintain the indifference condition, the second and third terms in Equation 6.10 must add up to zero. By referring to the reliability ratio definition in Equation 6.5, the following expression for reliability ratio (RR) can be derived as shown in Equation 6.12:

$$\text{RR} = \frac{\partial U/\partial \text{RM}}{\partial U/\partial \text{TT}} \cong \frac{X}{\text{RM} - \text{RM}_r} \tag{6.12}$$

This statement suggests that the reliability ratio can be estimated by dividing the certainty-equivalent additional travel time $X$ by how much the current reliability measure RM deviates from its reliable norm, $\text{RM}_r$. It should be noted that in general the second equality in Equation 6.12 is approximate.

However, in the case of the additive linear utility function Equation 6.6, this equality will be exact.

Note that the certainty-equivalent addition to average travel time ($X$) can be interpreted as an insurance premium. The policy ensures a reliable trip time with no (or tolerable) variation at the cost of adding $X$ units to the average travel time.

This is a very interesting result as it suggests that conceptually, RR can be stated as the ratio of two variables as opposed to being the ratio of two unknown model parameters that requires model calibration to determine their values. Furthermore, it should be noted that multiplying both sides of Equation 6.12 by VOT, the following expression for the value of reliability VOR is obtained as shown in Equation 6.13.

$$\text{VOR} \cong \frac{X}{\text{RM} - \text{RM}_r} \times \text{VOT} \tag{6.13}$$

However, note that the usefulness of this alternative approach hinges on access to good estimates of the additional certainty-equivalent travel time ($\hat{X}$). In general, finding a good estimate for $X$ based on the utility theory is not a straightforward problem.

The next section provides an alternative framework to approach the travel time reliability valuation problem. In transportation project evaluation and in travel behavior modeling in general, time can be viewed as the asset (with a corresponding capital value) that travelers invest into their trips going from Point A to Point B. An insurance policy that offers to compensate the traveler for variations in travel time is therefore an asset that would help travelers (investors) to control the risk associated with their travel times (capital investments). In this context, establishing the relationship between expected return and the risk measure is an essential part of any asset pricing theory.

A brief background on consumer theory in finance asset pricing models that are potentially useful for the problem at hand is provided. Asset pricing is a mature topic in economics and finance. This exposition of asset pricing is mainly from the perspective of consumption-based models (*4*).

## Consumption-Based Asset Pricing Model

The decision to take a trip can be viewed as an investment problem in which time is the essential asset travelers have. If the decision is to take a trip, then it means the individual has decided to invest a portion of their available time budget into the trip; in other words they have decided to consume their time in moving from Point A to Point B. By doing so, the traveler knowingly has reduced their available budget for initial consumption at Point A in the hope of gaining more utility by consuming their remaining time in a desirable activity later on at Point B. So, in a way, the trip decision involves a trade-off between consuming available time at the current Point A and moving to the new location (and losing some of the available time in the process) and consuming the remaining time (or portions of it) at Point B. In general, the decision is complicated by the fact that travel time from A to B is not deterministic. Expected and unexpected components of the travel time between A and B are both important to the decision makers. A traveler may be willing to build an extra amount of time into their trip (on top of what they expect the trip to take) to safeguard against variability in travel time. In fact, the payoff they will get at the end of their trip as a result of this decision is determined by the amount of time the actual trip time deviates from the guaranteed level.

At the decision point, the decision maker (traveler) must decide how much time they want to spend at the current location and, by moving to the new location, how much time they will have at the new location considering that moving from A to B introduces uncertainty in the amount of time that needs to be budgeted for the trip itself.

Figure 6.1 illustrates the consumption-based asset pricing model for a particular traveler. To formalize the rest of the discussion, let the traveler set aside (at time $t_0$) a budget of $B_0$ in equivalent monetary units for the trip. The traveler expects to spend $E(\tau)$ time units on this trip (with a value rate equal to the VOT) and is willing to spend an extra $X$ time units (with a value rate equal to the VOR) in order to buy the aforementioned insurance policy that guaranties them a reliable travel time. Therefore, the amount of budget left to be consumed initially ($c_0$) can be stated as shown in Equation 6.14.

$$c_0 = B_0 - \text{VOT} \times E(\tau) - \text{VOR} \times X \tag{6.14}$$

However, in general, as the trip takes place, the actual/realized travel time $\tau$ will include a $\Delta\tau$ time units deviation from the expected travel time $E(\tau)$ plus the additional allotted time $X$. See Equation 6.15.

$$\tau = E(\tau) + X + \Delta\tau \tag{6.15}$$

At the end of the trip, depending on how long it actually took the traveler to get to their destination, they may be left with a terminal budget $B_e$ and a payoff at a rate of $f_e(\Delta\tau)$ from the initial investment in the aforementioned insurance policy of the size $X$. See Equation 6.16.

$$c_e = B_e + f_e(\Delta\tau) \times X \tag{6.16}$$

The traveler's decision problem can be stated in terms of a utility maximization problem in which the objective is to maximize the utility of consumptions (of the traveler's time in activities other than the trip). Of course there is a distinction between consuming now and in the future and also between spending time at A or at B. So, in general the objective function

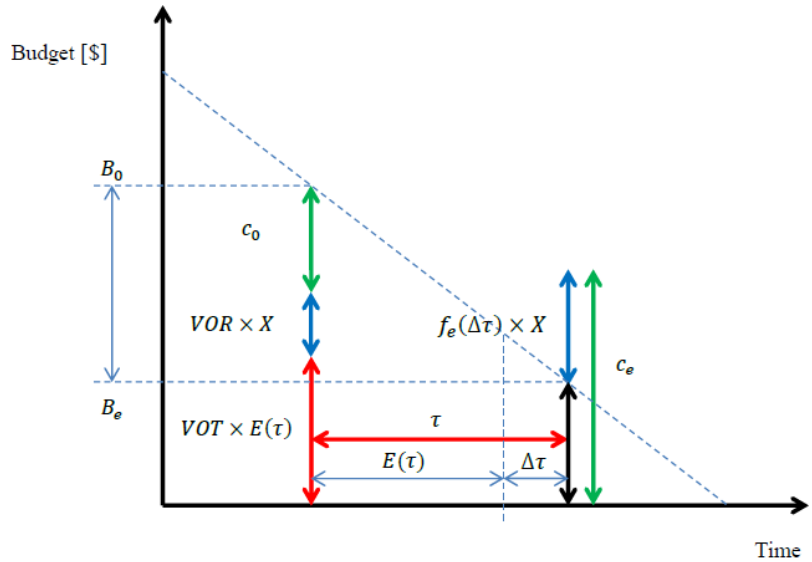


***Figure 6.1. Consumption-based asset pricing model depiction.***

is the sum of the utility of the initial consumption at Point A and the traveler's expectation of the discounted (with factor β) utility of consumption at the end of the trip at Point B as shown in Equation 6.17.

$$\max u_{A,0}(c_0) + E[\beta u_{B,e}(c_e)] \tag{6.17}$$

To solve Equation 6.17, subject to Equations 6.14 through 6.16, assuming regularity conditions on utility functions (mainly concavity due to a decision maker's risk averseness), it is possible to take the derivative of the objective function with respect to the additional time *X* and then set the derivative equal to zero as shown in Equation 6.18.

$$u'_{A,0}(c_0)c'_0 + E[\beta u'_{B,e}(c_e)c'_e] = 0 \tag{6.18}$$

Substituting the derivatives from Equations 6.14 and 6.16 into Equation 6.18, the following equality is derived as shown in Equation 6.19.

$$\text{VOR} \times u'_{A,0}(c_0) = E[\beta u'_{B,e}(c_e) f_e(\Delta\tau)] \tag{6.19}$$

Therefore, it is shown that under optimality conditions, the marginal utility loss of spending a little less time at the origin and buying a little more of the asset (insurance) should equal the marginal utility gain of spending a little more time at the destination in the future. Then value of reliability (VOR) may be stated as the expected value of the discounted payoffs scaled by the relative marginal utilities at the trip's origin and destination as shown in Equation 6.20.

$$\text{VOR} = E\left[\beta \frac{u'_{B,e}(c_e)}{u'_{A,0}(c_0)} f_e(\Delta\tau)\right] \tag{6.20}$$

Setting $\beta \frac{u'_{B,e}(c_e)}{u'_{A,0}(c_0)} = m$, the following expression for VOR is obtained as shown in Equation 6.21:

$$\text{VOR} = E[m f_e(\Delta\tau)] \tag{6.21}$$

Different asset pricing models are proposed for application in the case of nonlife insurance policy valuation. Each model makes certain assumptions about how the asset in question evolves over time to produce a distribution of different outcomes (Δτ) and how the payoffs $f_e(\Delta\tau)$ are determined. Also, they make assumptions on the discount factor *m* used to transform the value of payoffs at a future time to the current time. The most widely used asset pricing methods in practice that are also extensively studied in the literature include the following:

- Capital asset pricing model (CAPM) (*5,6*)
- Arbitrage pricing theory (APT) (*7*)
- Option pricing theory (OPT)

CAPM and APT are essentially linear-factor pricing models in which the discount and marginal utility growth expressions in the consumption-based model are replaced with a linear model of the form shown in Equation 6.22.

$$m = \beta \frac{u'_{B,e}(c_e)}{u'_{A,0}(c_0)} \cong a + b \times F \tag{6.22}$$

where *a* and *b* are parameters. Factor pricing models look for variables (*F*) that are good proxies for aggregate marginal utility growth. In the classic CAPM, the adopted factor is the return on the "wealth portfolio" (*11*).

In this project, option pricing theory is adopted to determine the value of travel time reliability (VOR). First, however, a brief overview of options and their applications in the interdisciplinary area of transportation economics is provided.

## What Is a Real Option?

Trigeorgis (*8*) gives the following concise definition of an option as a financial instrument: "An option is the right (not the commitment/obligation) to buy (if a call) or to sell (if a put) a specified asset (e.g. common stock) by paying a specified price (the exercise or strike price) on or before a specified date (the expiration or maturity date). If the option can be exercised before maturity, it is called an American option; if only at maturity, a European option."

However, the concept of insurance on travel time variability introduced here actually falls in the real options category. When the asset in question is tangible or real (as opposed to intangible financial instruments), the choices and decisions that come to existence in regard to operating and managing (such as altering, abandoning, expanding, shrinking, or deferring) that asset are commonly referred to as real options.

## Real Options in Transportation Projects

Garvin and Cheah (*9*) introduced the real options valuation techniques in the context of infrastructure investment decisions. They bring to light the fact that traditional project evaluation methods fundamentally fall short in taking into account the inherent uncertainty in cash flow and interest rates in their assumptions. Frequently, this leads to flawed evaluations and inappropriate investment decisions. They provide an interesting and somewhat detailed account of the Dulles Greenway (an early toll road project in Virginia that went into operation in 1995), whose forecast demand and income levels were not met. Project sponsors therefore had to renegotiate a plan for deferring debt payments and had to restructure the loan contracts with their creditors.

Pichayapan et al. (*10*) and Zhao et al. (*11*) use real options approaches to plan for highway investments under stochastic demand conditions. Saphores and Boarnet (*12*) analyzed the impact of uncertainty in population levels on optimal timing for investment in a congestion relief project. They considered the case of a linear city with fixed boundaries and a single CBD. It is shown that under certainty conditions, maximizing the utility of living in the city for its population is approximately equivalent to a standard benefit–cost analysis (BCA). However, when the urban population levels evolve as a stochastic process it is shown that, depending on the length of project implementation, optimal timings would vary considerably.

Vergara-Alert (*13*) proposes an extension of the real options theory for application in decisions regarding transportation projects. It is assumed both construction costs (outflows) and operating revenues (inflows) follow standard stochastic patterns. Then providing a different perspective, it is argued that the ratio of social operating revenues over construction costs can be modeled as a mean-reverting process that provides for improved modeling and description of real transportation finance cases.

Chow and Regan (*14, 15*) propose a mathematical optimization framework to incorporate deferral options in network level investment decision making. In their study, the source of stochasticity is random variations in O-D demand, which is exogenous to the problem. A variation of the Monte Carlo method originally proposed by Longstaff and Schwartz (*16*) (Least Squares Monte Carlo Simulation—LSM) was adopted to solve the resulting dynamic and stochastic network design problem. The method is applied to a small-size network but it does not scale up efficiently if the number of investment projects considered increases significantly. Another limitation of this method is that in the long run, despite evidence suggesting otherwise, O-D demands are not affected by congestion levels, travel time uncertainties, or infrastructure investments. Later they applied the model with some modifications to a larger network (*17*).

## Real Options in Trip and Route Choice Decision Making

Friesz et al. (*18*) introduce the idea of a European type congestion call option to value commuting to work along a given path for a given departure time selected by automobile drivers. Their treatment is based on the dynamic user equilibrium (DUE) concept in which drivers are modeled as Cournot-Nash noncooperative agents competing for limited roadway capacity when telecommuting from home is offered as an alternative to driving in a congested and unreliable network. Using a small network example, they show that offering a congestion call option to travelers may lower the net social costs of congestion.

## Real Options in Travel Time Reliability Valuation

To the best of our knowledge, there is only one reported case of applying Real Options methodology to the problem of travel time reliability valuation in the literature. A brief account of this application has been first reported by Puget Sound Regional Council (PSRC) (*19*) in the context of travel time reliability benefits estimation in a more general benefit–cost analysis setting. A more detailed account of this unique application is given in SHRP 2 Project L11 (*20*) and then summarized as a guidebook in Project L17 (*21*).

The reported application is based on the option-theoretic concept, which is a well-documented and comprehensively studied topic in the field of finance. While this is an innovative and bold application of a mature concept from finance into transportation economics, it has been met with criticism by some. These criticisms mainly stem from the fact that L11 failed to convey the option valuation process and its main ideas in a way that is accessible by other experts. Of course, using a closed-form solution built on a very specific set of assumptions about the underlying travel speed process and envisioned reimbursement policy did not provide a great deal of transparency. Besides, the fact that option characterization in Project L11 is based on speeds, and not travel times, raised serious questions about the justification of its application.

At the time the traveler decides to take a trip, they only have an idea about the trip time in terms of its expected travel time and some measure of its variation. If the traveler considers paying a premium in terms of leaving earlier (adding time to the expected travel time) in order to obtain insurance on the trip time (e.g., it will not deviate from a certain level or they will be compensated), then it is presumable that they will be willing to obtain the policy for the maximum possible duration of their trip to protect against the worst odds.

In general, the proposed method is very flexible and can be applied to a wide range of all possible conditions. In the next chapter, components of such a "hypothetical" travel time insurance policy are introduced and discussed. The components of the methodology that lead to the design of the travel time insurance policy and its valuation are discussed next.

CHAPTER 7

# Methodology

The methodology proposed to value travel time reliability based on option theory is described in this chapter. The proposed method is based on an analogy of a travel time insurance policy. The method applies historical travel time data over an extended period of time as input and performs the necessary analysis to identify variations that are experienced by travelers and, based on these variations, estimates a rational value for reliability that would be offered as the travel time insurance policy. In summary, to describe the method, the following questions need to be answered:

1. How can travel time evolutions over time be modeled?
2. How can a penalty/reward (payoff) of early/late arrivals at the destination be determined?
3. What is the guaranteed level of travel time?
4. What is the duration of time for which the travel time insurance policy is issued?
5. How do future payoffs get valued at the outset of trip?

Figure 7.1 illustrates the above-mentioned components of an option-theoretic valuation method. Note that this is a generic graphic. The methodology will be fully described by specifying each component in the following sections.

## Travel Time Evolution

Current research supports the notion that, at any given time, travel times are lognormally distributed (*22*) and that, over time, they represent a memory less Markov process (*43*). By definition, a continuous lognormally distributed process, which is also a Markov process, can be modeled using the geometric Brownian motion with drift (GBM) stochastic process (see Appendix E). This implies that changes in the continuous travel time process $\{\tau\}$ can be expressed as

$$d\tau = a\tau dt + \sigma\tau dz \qquad (7.1)$$

where $a$ and $\sigma$ are instantaneous drift (trend) and standard deviation parameters of the process, respectively.

Recalling Ito's lemma, the GBM process suggests that random variable $\tau$ is lognormally distributed with the following mean and variance at time $t$ when the initial time is denoted by $t_0$:

$$E[\tau(t)] = \tau(t_0)\exp\{a(t-t_0)\} \qquad (7.2)$$

$$V[\tau(t)] = \tau^2(t_0)\exp\{2a(t-t_0)\}\left(\exp\{\sigma^2(t-t_0)\}-1\right) \qquad (7.3)$$

For more information on the GBM stochastic process and relevant derivations, interested readers are referred to Appendix D.

## Random Walk Representation of Geometric Brownian Motion

The GBM process can be approximated by a discrete random walk. Set discrete time intervals equal to $\Delta t$ and increments of the log-travel time equal to

$$\Delta h = \sigma\sqrt{\Delta t} \qquad (7.4)$$

Then, the multiplicative step-up and step-down factors will be calculated as

$$u = \exp\left[\sigma\sqrt{\Delta t}\right] \qquad (7.5)$$

$$d = \exp\left[-\sigma\sqrt{\Delta t}\right] \qquad (7.6)$$

Respectively, probabilities of taking a step up or a step down in the random walk are given by

$$q = \frac{1}{2}\left[1 + \left(\left(a - \frac{\sigma^2}{2}\right)\Big/\sigma\right)\sqrt{\Delta t}\right] \qquad (7.7)$$

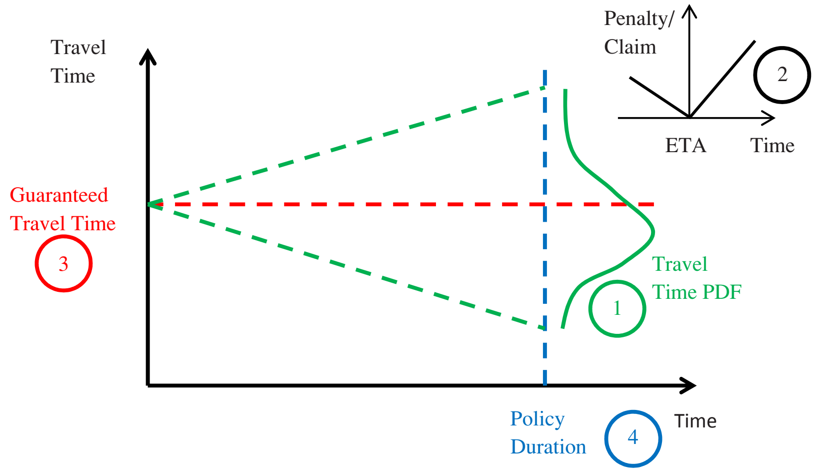


***Figure 7.1. Various components of a travel time insurance pricing method.***

$$q' = 1 - q = \frac{1}{2}\left[1 - \left(\left(a - \frac{\sigma^2}{2}\right)\Big/\sigma\right)\sqrt{\Delta t}\right] \quad (7.8)$$

Then, it can be shown that over any $T$ time units ($T = n\Delta t$), the expected and variance of log-travel time changes (a binomial distribution) can be expressed as

$$E[\log(\tau(T)) - \log(\tau(0))] = n(q - q')\Delta h = \left(a - \frac{\sigma^2}{2}\right)T \quad (7.9)$$

$$V[\log(\tau(T)) - \log(\tau(0))] = n\left[1 - (q - q')^2\right](\Delta h)^2$$
$$= \left[1 - \left(\left(a - \frac{\sigma^2}{2}\right)\Big/\sigma\right)^2 \Delta t\right]T\sigma^2 \quad (7.10)$$

In the limit, as time steps become smaller ($\Delta t \to 0$), the mean and variance of the travel time displacement from its initial value as described by the random walk will be equal to the following:

$$E[\log(\tau(T))] = \log(\tau(0)) + \left(a - \frac{\sigma^2}{2}\right)T \quad (7.11)$$

$$V[\log(\tau(T)/\tau(0))] = \sigma^2 T \quad (7.12)$$

Note that both mean and variance of the random walk in the limit are independent of the adopted discretization stencil ($\Delta t$ &$\Delta h$).

## Example 1

To illustrate the above concepts, a simple example is presented in which travel time variations are modeled as a GBM stochastic process with instantaneous trend and standard deviation parameters equal to 5 and 10%, respectively.

Figure 7.2 illustrates a realization of such process over the next 20 minutes when initial travel time is equal to 10 minutes. The travel time realization shown in blue is only one instance (out of an infinite number of instances) that travel time could have evolved under the assumption of this particular GBM process. The solid red line represents the travel time trend and at any time $T$ can be expressed by

$$E[\tau(T)] = 10\exp(0.05T) \quad (7.13)$$

Similarly, the pair of dashed red lines in Figure 7.2 represents the lower and upper 95% confidence intervals around the mean of the process. The variance of travel time at any time $T$ is given by

$$V[\tau(T)] = 10^2\exp(2\times 0.05T)[\exp(0.1^2 T) - 1]$$
$$= 100[\exp(0.11T) - \exp(0.1T)] \quad (7.14)$$

The random walk representation of this process at 2-minute increments ($\Delta t = 2$) can be built as a binomial tree with $\left(\Delta h = 0.1\sqrt{2} \cong 0.14\right)$ increments in the $y$-axis with a logarithmic scale. However, in the normal travel time scale, the multiplicative step-up and step-down factors will be equal to

$$u = \exp(0.14) = 1.15 \quad (7.15)$$

$$d = 1/u = \exp(-0.14) = 0.87 \quad (7.16)$$

With the following probabilities associated with step-up and step-down moves, respectively:

$$q = \frac{1}{2}\left[1 + \left(\frac{0.05 - \frac{0.1^2}{2}}{0.1}\right)\sqrt{2}\right] \cong 0.82 \quad (7.17)$$

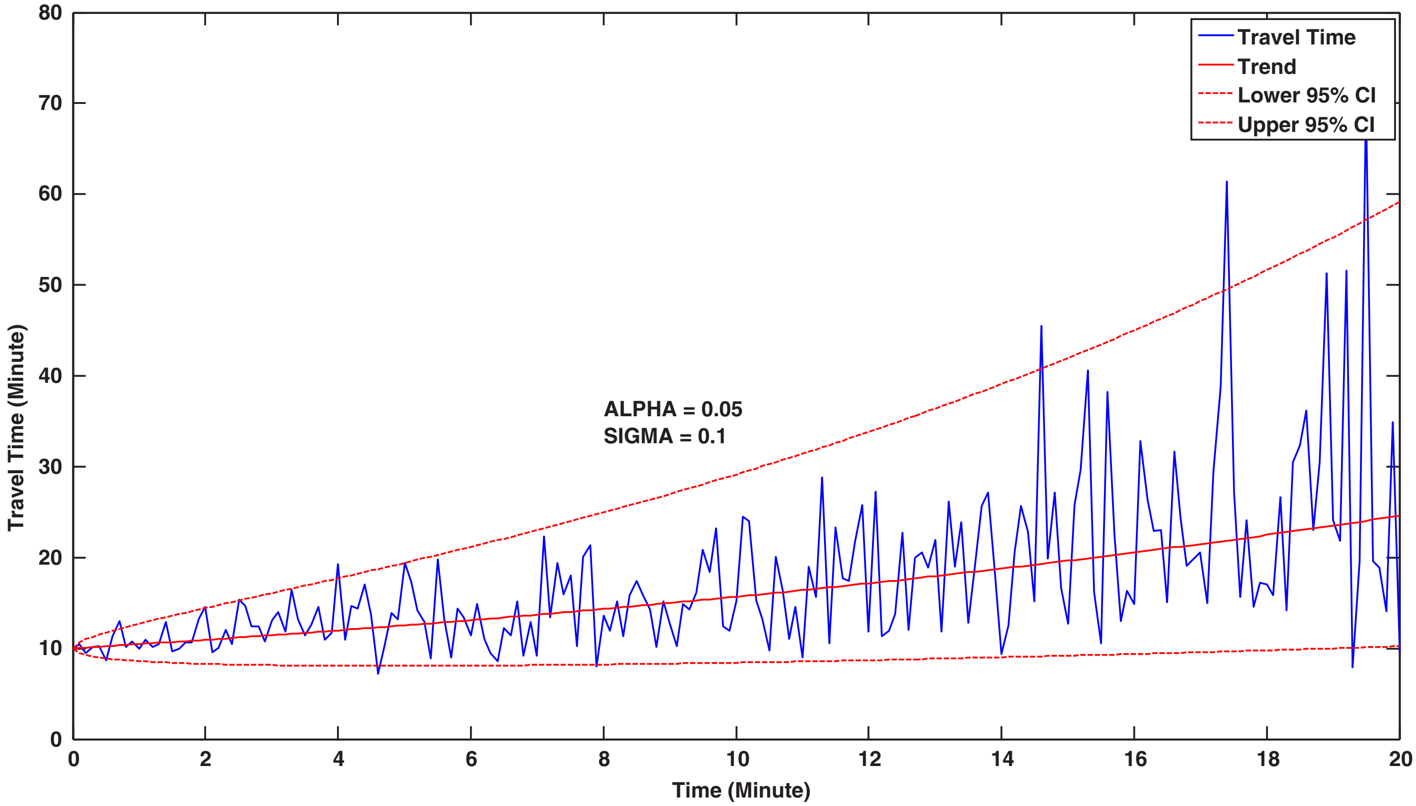


***Figure 7.2. Sample travel time evolution path simulated as geometric Brownian motion (GBM) process.***

$$q' = 1 - 0.82 \cong 0.18 \quad (7.18)$$

Also, the expectation and variance of log-travel times at any time step ($T = n\Delta t$) will be given by the following expressions:

$$E[\log(\tau(T))] = \log(10) + \left(0.05 - \frac{0.1^2}{2}\right)T \cong 2.30 + 0.045T \quad (7.19)$$

$$V[\log(\tau(T)/10)] = \left[1 - \left(\left(0.05 - \frac{0.1^2}{2}\right)\Big/0.1\right)^2 2\right](0.1^2)T$$
$$= 0.00595T \quad (7.20)$$

Similarly, at 1-minute time increments ($\Delta t = 1$), the relevant parameters of the corresponding binomial tree representation will be the following:

$$\Delta h = 0.1\sqrt{1} = 0.1 \quad (7.21)$$

$$u = \exp(0.1) = 1.11 \quad (7.22)$$

$$d = 1/u = \exp(-0.1) = 0.90 \quad (7.23)$$

$$q = \frac{1}{2}\left[1 + \left(\frac{0.05 - \frac{0.1^2}{2}}{0.1}\right)\sqrt{1}\right] = 0.725 \quad (7.24)$$

$$q' = 1 - 0.725 = 0.275 \quad (7.25)$$

$$E[\log(\tau(T))] = \log(10) + \left(0.05 - \frac{0.1^2}{2}\right)T \cong 2.30 + 0.045T \quad (7.26)$$

$$V[\log(\tau(T)/10)] = \left[1 - \left(\left(0.05 - \frac{0.1^2}{2}\right)\Big/0.1\right)^2 1\right](0.1^2)T$$
$$= 0.007975T \quad (7.27)$$

## Payoff Characterization

It is conceivable that travelers would normally incur a penalty as a result of arriving later or earlier than scheduled at their destination. Under the current analogy with an insurance policy, the travelers who obtain the option at the start of their trip will be reimbursed for any penalty they incur at the termination of their trip due to deviation of their actual arrival time at the destination from their expected arrival time. In this section a general framework for characterization of such hypothetical payoffs is presented.

It should be noted that in the scheduling approach (*23, 24*) to activity decision making, time spent in travel between origin and destination, the magnitudes of lateness and earliness at the destination compared with the preferred time of arrival PTA are introduced in a linear-additive form to specify trip utility. Of course, this is a simple specification of the utility in which trip costs and additional terms are ignored.

$$U(t_0, \tau|\text{PTA}) = a \cdot \tau + \beta \cdot (t_0 + \tau - \text{PTA})^- + \gamma \cdot (t_0 + \tau - \text{PTA})^+ + \theta \cdot DL \qquad (7.28)$$

The scheduling preference expressed by Equation 7.28 is often referred to as (α, β, γ) model. Extending this activity scheduling approach to explicitly include the uncertainty of travel time, and then minimizing the expected disutility for a traveler, estimates of optimal departure time $t_0^*$, VOT, and VOR may be obtained (*25, 26*). The scheduling approach provides insight into the relationships between the value of travel time reliability and theoretical or empirical travel time distributions (*27*). One important result of this analysis is the first-order condition for optimal departure time in the special case $\theta = 0$ (*28, 29*):

$$P_L^* = \frac{\beta}{\beta + \gamma} \qquad (7.29)$$

where $P_L^*$ is the optimal probability of being late. In the United States, a choice of $P_L^* = 0.05$ is consistent with selection of 95th percentile travel time to determine buffer time travelers add to their average travel times (*30*). This leads to the interesting result that being 1 minute late is almost 19 times as negatively perceived as being 1 minute early ($\gamma \cong 19\beta$) by an average traveler.

Similar to the scheduling approach, in this study the penalty associated with arriving late or early is assumed to mainly depend on the departure time $t_0$, actual travel time τ, and preferred time of arrival PTA. In general, additional factors such as trip purpose TP and traveler's socioeconomics SE can also be introduced in the payoff model.

$$C(\tau|t_0) = f(t_0 + \tau - \text{PTA}, \text{TP}, \text{SE}) \qquad (7.30)$$

For a given trip purpose and an individual traveler (constant last two arguments), the simple linear-additive expression for payoff conditioned on departing at $t_0$ with a fixed PTA can be written as

$$C(\tau|t_0) = \beta(t_0 + \tau - \text{PTA})^- + \gamma(t_0 + \tau - \text{PTA})^+ \qquad (7.31)$$

For brevity purposes, by explicitly noting that cost of travel depends on departure time $t_0$, let us drop the conditional and set PTA = $t_0 + E(\tau)$, which suggests the traveler ignores the unreliability of travel time and budgets only the expected travel time for their trip. This makes sense in this context since the traveler is assumed to have obtained an insurance policy that provides full protection against potentially negative impacts of travel time variations. Finally, let's express unit earliness and lateness costs as coefficients of VOT:

$$C(\tau) = \left[a \cdot (\tau - E(\tau))^- + b \cdot (\tau - E(\tau))^+\right] \cdot \text{VOT} \qquad (7.32)$$

Note that the above payoffs are, in fact, retroactively calculated meaning that initially the realized travel time (τ) and therefore its corresponding payoff ($C(\tau)$) is not known to the traveler. This implies that the cost statements discussed in this section are only applicable at the end of the insurance policy validity period. Provided that the insurance policy covers a period longer than the actual travel time experienced by the traveler, the cost associated with travel time variability around its expected value after its realization can be obtained by the following expression:

$$C_N(\tau) = \left[a \cdot (\tau(T) - E(\tau))^- + b \cdot (\tau(T) - E(\tau))^+\right] \cdot \text{VOT} \qquad (7.33)$$

where $C_N$ denotes the cost associated with travel time variability as calculated at the termination of the insurance policy period (time step $N$). In most practical cases, it is expected that $b$ is positive while $a$ may assume negative values (for instance when arriving early is incentivized). Also, it is reasonable to expect $b$ to be larger than $a$ ($b \gg a$), since the cost of being late is usually much larger than the cost of being early.

Figure 7.3 illustrates the general bilinear form of the above cost function in which normalized costs are depicted versus deviation of travel time from its expected value. It should be noted that, in general, the cost function can take any form.

Figure 7.4 depicts the common sense constraints on magnitudes of cost parameters $a$ and $b$ as well as their feasible region. As noted earlier, the left half of the feasible region ($a < 0$) is indicative of situations in which early arrivals are rewarded as, for instance, in the case of work trips when travelers start getting paid as soon as they get to their workplace no matter how early they are.

In this research it is assumed that $b = 1$, which indicates the cost of being late is equal to the value of extra time (compared with the expected time) the traveler has spent on the road. This is a conservative assumption since it does not account for

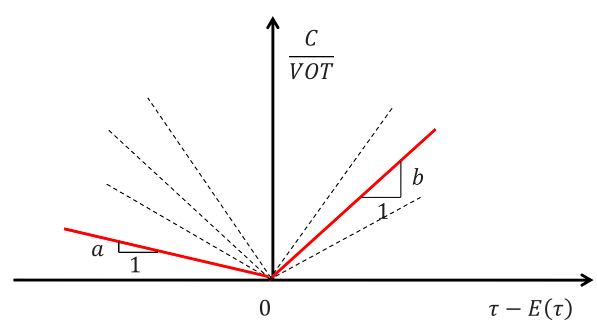


***Figure 7.3. Bilinear payoff function.***

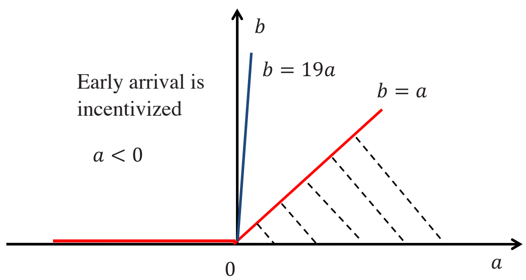


*Figure 7.4. Space of normalized early and late arrival perceived costs.*

the wages lost, impacts of schedule disruptions, and negative reactions by other parties involved (e.g., boss at work, teacher at school, friends and relatives). Therefore, from what we know about the average traveler's relative perceived costs of being late or early, $a$ is estimated to be negligible ($a \cong 1/19 \cong 0.05$) for practical purposes.

It is widely believed that VOT for local personal and business travel in the United States is about 50 and 100% of the wage rate, respectively (*31*). Therefore, in the case of work trips in which arriving late would reduce travelers' income proportional to the amount of time they are late, $b = 2$ would be more realistic ($a \cong 2/19 \cong 0.1$).

## Guaranteed Travel Time

Travel time unreliability is measured as the variability around the mean travel time. Therefore, it is common sense to assume that a guaranteed level of any travel time insurance policy designed to protect travelers from unreliability of their trip time must be the expected travel time (its mean or average). This is also in line with the previous definition of payoff function at the termination of the travel time insurance policy.

Note that the proposed methodology is able to deal with any other level of travel time as the guaranteed value. The choice to proceed with expected travel time as the guaranteed level of insurance policy is based on the current understanding and interpretation of reliability as perceived by travelers. This selection is not a limitation for this method and can be relaxed as soon as another desirable level or range of levels for guaranteed travel times are deemed as more reasonable.

## Duration of Travel Time Insurance Policy

It is customary to assume that the threshold between recurring and nonrecurring traffic congestion falls somewhere between 80th and 95th percentiles of a travel time distribution. This means that on average, 5–20% of the trip times are subject to nonrecurrent disturbances (e.g., incidents, weather events). While this probability may be different in any particular case, on average for well-designed, well-maintained, and carefully operated surface facilities with traffic incident management practices in place, the 5% percent risk level in encountering nonrecurrent congestion seems more acceptable.

The insurance policy duration adopted in this research reflects the maximum conceivable duration of travel time as a result of recurrent congestion. The 95th percentile travel time is again a conservative choice as it, in effect, creates a policy long enough for any trip impacted by recurrent congestion to be compensated after the trip is terminated.

Again, it should be noted that the proposed method is able to deal with any other policy duration and by no means is restricted to the particular duration selected in this research.

## Certainty-Equivalent Payoff Valuation

So far, we know how payoffs at the termination of the insurance policy duration are calculated. But, we still need to answer the question of how the payoffs will be valued at the start of the trip. To answer this question, first we need to define under what conditions travel time and its variations would be considered as reliable.

Figure 7.5 shows a branch of the binomial tree that is used to represent the random walk approximating a GBM process that models travel time ($\tau$) variations. The top branch illustrates the random walk in terms of travel time logarithms where in one time step the current logarithm gets incremented up and down by complementary probabilities

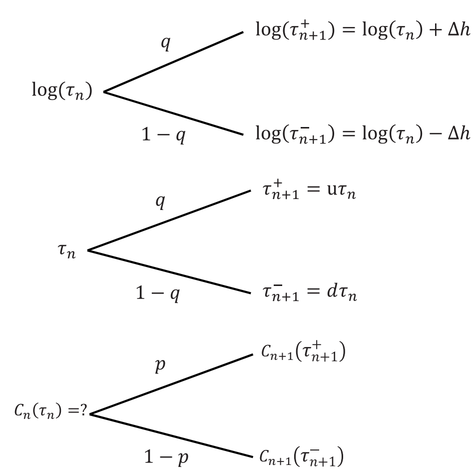


*Figure 7.5. A binary branch of the binomial tree representing travel time variations as a random walk.*

$p$ and $1 - p$, respectively. The middle branch is a rescaled version of the top branch where all travel times are expressed in unit time scale. From a traveler's perspective, at the start node of this branch, travel times in the next time step will be considered as reliable only if they expect them to vary within a certain range around its current value. The expected next-step travel time can be simply calculated as the weighted average of the binary next-step travel times:

$$E(\tau_{n+1}|\tau_n) = p \cdot (u\tau_n) + (1-p) \cdot (d\tau_n) \quad (7.34)$$

Note that at this point, unlike process probabilities ($q$ and $1 - q$), the certainty-equivalent probabilities (weights, $p$ and $1 - p$) used in calculation of the above expectation are not known. Also, the certainty condition can be expressed as

$$|E(\tau_{n+1}|\tau_n) - \tau_n| \leq \tau_n \cdot r \cdot \Delta t \quad (7.35)$$

where certainty threshold $r$ is defined as a percentage rate of the current travel time and the size of time step. In practice this certainty threshold can be assumed to be small ($r \leq 5\%$). For instance, when the current trip time is 40 minutes, the travel time is deemed as reliable when, in the next 5 minutes, it is still within the range of 40 ± 10 minutes.

Expanding Equation 7.35 as inequality pairs and substituting for expected future travel time from Equation 7.34, the following expressions are obtained:

$$\tau_n \cdot (1 - r \cdot \Delta t) \leq E(\tau_{n+1}|\tau_n) \leq \tau_n \cdot (1 + r \cdot \Delta t) \quad (7.36)$$

$$1 - r \cdot \Delta t \leq p \cdot u + (1-p) \cdot d \leq 1 + r \cdot \Delta t \quad (7.37)$$

Note that Equation 7.37 is not dependent on travel times as they cancel out from both sides of inequalities. This gives a range for binary probabilities that would ensure certainty conditions in travel time:

$$\frac{1 - d - r \cdot \Delta t}{u - d} \leq p \leq \frac{1 - d + r \cdot \Delta t}{u - d} \quad (7.38)$$

For small tolerance rates ($r \cong 0$), or in general when the time steps are small ($\Delta t \to 0$), or simply if the midrange probability is targeted, the certainty-equivalent probability is expressed as

$$p = \frac{1 - d}{u - d} \quad (7.39)$$

And, thus:

$$1 - p = \frac{u - 1}{u - d} \quad (7.40)$$

Now that certainty-equivalent probabilities are specified, they can be used to value previous step payoffs by taking their certainty-equivalent expectation:

$$C_n(\tau) = p \cdot C_{n+1}(u\tau) + (1-p) \cdot C_{n+1}(d\tau), n = 0, 1, 2, \ldots, N-1 \quad (7.41)$$

In Figure 7.5, the bottom branch depicts the end point payoffs and the certainty-equivalent probabilities that are specified by Equations 7.41 and 7.39, respectively. In the case where the binomial tree has multiple time steps, the same process can be repeated recursively to calculate intermediate and initial certainty-equivalent values for the terminal payoffs. The proposed valuation process, in the context of binomial trees, is designed to reflect the certainty that the insurance policy creates for its holders (travelers).

CHAPTER 8

# Summary

Table 8.1 summarizes the reliability valuation method described in previous chapters. For data input, the method uses field measurements of travel time in the form of an ordered data set (time series) as well as an estimate of VOT. In the proposed method, average and 95th percentile travel times are used as the guaranteed travel time level and policy duration, respectively.

In order to run hypothesis testing for a GBM stochastic process, travel time series need to be transformed to a logarithmic scale and then get differenced once. Then, based on the transformed series, trend and standard deviation parameters can be estimated. The GBM hypothesis testing is carried out on the transformed series using a chi-square statistic to verify whether the series is normally distributed.

After establishing the validity of using a GBM process to model travel time variations, a binomial tree can be formed to represent its approximate random walk process. The binomial tree is specified by the number and length of time steps as well as the size of log-travel time increments and up and down move probabilities.

Once the binomial tree is specified, terminal payoffs at all nodes on the last time step are estimated. Then, certainty-equivalent probabilities are calculated. These probabilities are then used to carry out expectation calculations at the binary ends of each branch and to evaluate policy values at all intermediate and initial nodes of the binomial tree. The estimated value at the initial node is the VOR and by dividing it over VOT, the reliability ratio (RR) can be estimated.

Table 8.2 summarizes all the parameters used in the proposed method. As was discussed, lateness and earliness parameters are set equal to 1 and 0.05, respectively. This choice indicates the relative cost perceptions of being late and being early based on experience in U.S. urban areas. The travel time insurance policy is designed to provide guaranteed travel times at the average travel time level and to have a lifetime equal to 95th percentile of travel time distribution to cover all recurrent congestion cases. The threshold to define certainty (limit on variations) in travel time is set strictly at 0%.

## Comparison Between the Proposed Approach and the SHRP 2 Project L11 Methodology

Table 8.3 provides a side-by-side comparison between the proposed approach in this study and the L11 methodology. Both approaches take advantage of the analogy between value of travel time reliability and an insurance policy that guarantees a specific level of travel time for a specific duration of time. While the L11 method was criticized for discounting speeds, the proposed approach in this study directly works with travel times, which, in the transportation literature, are commonly associated with cost. The stochastic process adopted in both methods are essentially the same, but this study uses the binomial tree representation of a discrete random walk. This choice gives the proposed method a tremendous level of flexibility in dealing with any conceivable scenario in terms of payoffs and, more importantly, provides insight into the evaluation process. Whereas the L11 approach was more like a black box, the proposed method can be tweaked carefully to fit new circumstances and any theoretical/empirical evidence that may become available.

### Example 2

Building on the GBM process described in Example 1 in Chapter 7, we would like to build the binomial tree structure and to estimate the terminal payoffs. Then based on the reliability and variation threshold arguments provided earlier, certainty-equivalent probabilities as well as intermediate and current values of reliability will be calculated.

First, let us assume the 95th percentile travel time is 20 minutes. The only case presented here is when 2-minute time intervals ($\Delta t = 2$) are considered. In that case, the forward GBM factors and probabilities (Equations 7.15 through 7.17) are used to build the binomial tree presented in Table 8.4. Also, Table 8.5 summarizes the results of recursive valuation

***Table 8.1. Summary of the Proposed Travel Time Data-Driven Method for Estimating VOR/RR***

| Step | Description |
|---|---|
| Input | Travel time series (time ordered data set)<br>Value of time (VOT) |
| Primary Calculations | Travel time distribution (frequency of observations, unordered data set)<br>• Average travel time<br>• 95th percentile travel time |
| Stochastic process | One-difference lognormal transform of travel time series<br>• Average<br>• Standard deviation<br>Trend and standard deviation parameter estimates<br>Hypothesis testing for GBM |
| Binomial tree | Number and length of time steps<br>Increment size<br>Up and down probabilities |
| Payoff | Terminal step calculations |
| Valuation | Certainty-equivalent probabilities<br>Intermediate and initial values |
| Output | Value of reliability (VOR)<br>Reliability ratio (RR) |

of reliability. In this case, the set of certainty-equivalent probabilities used are calculated as follows:

$$p=\frac{1-0.87}{1.15-0.87}=0.46 \qquad (8.1)$$

And, thus

$$1-p=1-0.46=0.54 \qquad (8.2)$$

Table 8.4 shows the binary tree constructed to represent the aforementioned GBM process as time step (columns) increments from left to the right. Travel time has time units and therefore note should be taken in interpreting the GBM process values. The reported values indicate travel time over

***Table 8.2. Parameters Used in the Proposed Approach***

| Description | Parameter | Value |
|---|---|---|
| Lateness parameter | *b* | 1 |
| Earliness parameter | *a* = *b*/19 | 0.05 |
| Guaranteed travel time | Average | |
| Policy duration | 95th percentile | |
| Certainty threshold rate | *r* | 0% |

Note: empty cells = to be determined based on data.

***Table 8.3. Comparison Between Project L11 Methodology and Proposed Approach***

| Method | L11 | Proposed Approach |
|---|---|---|
| Analogy used? | Insurance premium | Insurance premium |
| What is being insured? | Average speed | Average travel time |
| Policy duration? | 95th percentile trip time | 95th percentile trip time |
| Stochastic process | GBM (continuous) | Binomial tree (discrete) |
| Payoff? | Speeds lower than average | Lateness/earliness penalty |
| Valuation? | Discounted value | Certainty-equivalent value |
| Solution type? | Closed form (Black-Scholes) | Numerical simulation |

the same link as time passes. In this representation, each cell is identified by the time elapsed since the start of process (column header) and the travel time level (row entries). For instance, at initial time ($T=0$), link travel time is 10 minutes, and 2 minutes later ($T=2$), travel time on the same link can be either 11.5 or 8.7 minutes.

Note that travel time increments between two adjacent rows are not uniform as the travel times are reported in their normal scale (minutes). Had travel times been reported in logarithmic scale then rows would have been uniformly spaced from each other. The modeled travel times at the termination of the simulation (rightmost column) can be used to calculate payoffs.

Payoff calculation at the termination of the period for which the travel time insurance policy has been valid ($T=20$) is performed using

$$C_N(\tau_N)=\left[0.05\times(\tau_N-10)^{-}+1\times(\tau_N-10)^{+}\right]\times \text{VOT} \qquad (8.3)$$

For instance, in the case of highest possible travel time at termination (40.5 minutes) the payoff is

$$C_{10}(40.5)=\left[0.05\times(40.5-10)^{-}+1\times(40.5-10)^{+}\right] \times \text{VOT}=30.5\times \text{VOT} \qquad (8.4)$$

And in the case of smallest possible travel time at termination (2.5 minutes) the payoff is

$$C_{10}(2.5)=\left[0.05\times(2.5-10)^{-}+1\times(2.5-10)^{+}\right] \times \text{VOT}=0.38\times \text{VOT} \qquad (8.5)$$

***Table 8.4. Forward Time Binary Tree Construction (a = 5%, $\sigma$ = 10%, $\Delta t = 2$, $\tau(0) = 10$, $\tau_{95} = 20$)***

| $n = 0$ | $n = 1$ | $n = 2$ | $n = 3$ | $n = 4$ | $n = 5$ | $n = 6$ | $n = 7$ | $n = 8$ | $n = 9$ | $n = 10$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **$T = 0$** | $T = 2$ | $T = 4$ | $T = 6$ | $T = 8$ | $T = 10$ | $T = 12$ | $T = 14$ | $T = 16$ | $T = 18$ | **$T = 20$** |
| | | | | | | | | | | **40.5** |
| | | | | | | | | | 35.2 | |
| | | | | | | | | 30.6 | | **30.6** |
| | | | | | | | 26.6 | | 26.6 | |
| | | | | | | 23.1 | | 23.1 | | **23.1** |
| | | | | | 20.1 | | 20.1 | | 20.1 | |
| | | | | 17.5 | | 17.5 | | 17.5 | | **17.5** |
| | | | 15.2 | | 15.2 | | 15.2 | | 15.2 | |
| | | 13.2 | | 13.2 | | 13.2 | | 13.2 | | **13.2** |
| | 11.5 | | 11.5 | | 11.5 | | 11.5 | | 11.5 | |
| **10** | | 10 | | 10 | | 10 | | 10 | | **10** |
| | 8.7 | | 8.7 | | 8.7 | | 8.7 | | 8.7 | |
| | | 7.6 | | 7.6 | | 7.6 | | 7.6 | | **7.6** |
| | | | 6.6 | | 6.6 | | 6.6 | | 6.6 | |
| | | | | 5.7 | | 5.7 | | 5.7 | | **5.7** |
| | | | | | 5.0 | | 5.0 | | 5.0 | |
| | | | | | | 4.3 | | 4.3 | | **4.3** |
| | | | | | | | 3.8 | | 3.8 | |
| | | | | | | | | 3.3 | | **3.3** |
| | | | | | | | | | 2.9 | |
| | | | | | | | | | | **2.5** |

Note: $\Delta h = 0.14$, $u = 1.15$, $d = 0.87$, $q = 0.82$.

At the intermediate and initial time steps ($n = 0, 1, 2, \ldots, 9$), by taking the expectations recursively and using certainty-equivalent probabilities, reliability values can be estimated using the following expression:

$$C_n(\tau) = 0.46 \times C_{n+1}(u\tau) + 0.54 \times C_{n+1}(d\tau), \quad n = 0,1,2,\ldots,9 \qquad (8.6)$$

For instance, after 18 minutes ($T = 18$), if travel time is 35.2 minutes, the insurance premium the traveler is willing to pay in order to guarantee travel time at 10 minutes in the next 2 minutes is equal to

$$C_9(35.2) = [0.46 \times 30.5 + 0.54 \times 20.6] \times \text{VOT}$$
$$= 25.15 \times \text{VOT} \qquad (8.7)$$

Table 8.5 summarizes the recursive reliability values obtained at all terminal, intermediate, and initial steps along the binary tree. The reported numbers are normalized values by VOT amount. In other words, these numbers are, in fact, the reliability ratio (RR) times average travel time (TT) at all nodes on the tree. Of course, in the case of travel times, the only important value is the initial value (1.71 in this case).

***Table 8.5. Recursive Reliability Valuation (*a = *0.05,* b = *1,* r = *0%,* Δt = *2,* E*(τ) = 10,* $\tau_{95}$ *= 20)***

| *n* = 0 | *n* = 1 | *n* = 2 | *n* = 3 | *n* = 4 | *n* = 5 | *n* = 6 | *n* = 7 | *n* = 8 | *n* = 9 | *n* = 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| ***T* = 0** | *T* = 2 | *T* = 4 | *T* = 6 | *T* = 8 | *T* = 10 | *T* = 12 | *T* = 14 | *T* = 16 | *T* = 18 | ***T* = 20** |
| | | | | | | | | | | **30.5** |
| | | | | | | | | | 25.15 | |
| | | | | | | | | 20.51 | | **20.6** |
| | | | | | | | 16.48 | | 16.55 | |
| | | | | | | 12.99 | | 13.05 | | **13.1** |
| | | | | | 9.96 | | 10.02 | | 10.08 | |
| | | | | 7.39 | | 7.38 | | 7.43 | | **7.5** |
| | | | 5.31 | | 5.21 | | 5.13 | | 5.18 | |
| | | 3.71 | | 3.54 | | 3.36 | | 3.18 | | **3.2** |
| | 2.53 | | 2.34 | | 2.12 | | 1.85 | | 1.47 | |
| **1.71** | | 1.53 | | 1.32 | | 1.06 | | 0.71 | | **0** |
| | 1.01 | | 0.84 | | 0.64 | | 0.39 | | 0.06 | |
| | | 0.56 | | 0.43 | | 0.28 | | 0.12 | | **0.12** |
| | | | 0.33 | | 0.25 | | 0.18 | | 0.17 | |
| | | | | 0.25 | | 0.22 | | 0.22 | | **0.22** |
| | | | | | 0.26 | | 0.26 | | 0.26 | |
| | | | | | | 0.29 | | 0.29 | | **0.29** |
| | | | | | | | 0.32 | | 0.32 | |
| | | | | | | | | 0.34 | | **0.34** |
| | | | | | | | | | 0.36 | |
| | | | | | | | | | | **0.38** |

Note: $p = 0.46$.

CHAPTER 9

# Value of Reliability Savings Quantification

In classic utility-based reliability valuation, using the reliability ratio concept (Equation 6.5), value of travel time reliability (VOR) is equal to value of time (VOT) multiplied by the reliability ratio (RR).

$$\text{VOR} = \text{RR} \times \text{VOT} \tag{9.1}$$

This simple relationship gives an estimate of the value of reliability (VOR) for each unit of the reliability measure (RM). Therefore, cost of reliability (RC) can be linearly estimated by multiplying the unit value of reliability (VOR), the RM, and the number of users affected ($V$) of the road segment under consideration.

$$\text{RC} = \text{VOR} \times \text{RM} \times V = \text{RR} \times \text{VOT} \times \text{RM} \times V \tag{9.2}$$

Reliability savings of an improvement can be estimated as the difference between reliability costs in the before and after scenarios ($\Delta\text{RC} = \text{RC}_b - \text{RC}_a$). Assuming the value of reliability (VOR) remains unchanged before and after the improvement, the reliability savings can be estimated as the following:

$$\Delta\text{RC} = (\text{RR} \times \text{VOT}) \times (\text{RM}_b \times V_b - \text{RM}_a \times V_a) \tag{9.3}$$

Note that $b$ and $a$ subscripts used in this chapter indicate the before and after scenarios of the improvement under consideration, respectively.

Plugging the certainty-equivalent estimate of the reliability ratio according to utility theory (Equation 6.12) into the reliability cost estimate (Equation 9.2) results in the following expression for reliability cost estimation:

$$\text{RC} = X \times \text{VOT} \times \frac{\text{RM}}{\text{RM} - \text{RM}_r} \times V \tag{9.4}$$

Note that in case the reliability measure used takes a value equal to or near zero under reliable conditions ($\text{RM}_r \cong 0$), then the reliability cost estimate expression can be further simplified as

$$\text{RC} = X \times \text{VOT} \times V \tag{9.5}$$

For instance, standard deviation and buffer index are the reliability measures that meet this condition. In these cases, the reliability savings of an improvement can be estimated as the following:

$$\Delta\text{RC} = (X \times \text{VOT}) \times (V_b - V_a) \tag{9.6}$$

Note that the certainty-equivalent based reliability cost expression (Equation 9.5) can be rewritten as

$$\text{RC} = \frac{X}{\text{TT}} \times \text{VOT} \times \text{TT} \times V \tag{9.7}$$

Comparing Equations 9.2 and 9.7 implies an analogy between utility-based and certainty-equivalent based reliability cost estimates. In fact, in the certainty-equivalent approach, the ratio of certainty-equivalent addition to the average travel time ($X$) and average travel time (TT) is analogous to the reliability ratio (RR):

$$\text{RR} = \frac{X}{\text{TT}} \tag{9.8}$$

This may become more evident if both nominator and denominator in Equation 9.8 are both multiplied by VOT and $V$. The nominator in this case will represent the reliability cost (RC), and denominator will be equal to the cost of average travel time (TC):

$$\text{RR} = \frac{X \times \text{VOT} \times V}{\text{TT} \times \text{VOT} \times V} = \frac{\text{RC}}{\text{TC}} \tag{9.9}$$

Note that the option-based reliability value Equation 7.41 can be expressed as the product of a certainty-equivalent additional travel time ($X$) and value of time (VOT):

$$C_0 = X \times \text{VOT} \tag{9.10}$$

Therefore, substituting the option-based reliability value into the reliability cost estimate (Equation 9.5) will result in the following simple expression:

$$RC = C_0 \times V \tag{9.11}$$

And, substituting the certainty-equivalent additional travel time ($X$) from Equation 9.10 into Equation 9.8, the reliability ratio (RR) can be expressed as the following:

$$RR = \frac{C_0/VOT}{TT} = \frac{C_0}{TC} \tag{9.12}$$

Note that the option-based reliability value ($C_0$) is dependent on the average travel time (TT). Therefore, in the option-based approach, reliability savings due to an improvement in general are calculated as

$$\Delta RC = C_{0,b} \times V_b - C_{0,a} \times V_a \tag{9.13}$$

Using the more expansive expression of certainty-based reliability cost (Equation 9.7), the reliability savings due to an improvement can be expressed as

$$\Delta RC = (RR_b \times TT_b \times V_b - RR_a \times TT_a \times V_a) \times VOT \tag{9.14}$$

CHAPTER 10

# Corridor Methodology Example Applications

In this chapter the application of the proposed methodology using real-world cases is presented. Five major corridors in the state of Maryland are selected for the analysis. These cases include three major north-south corridors running parallel to each other between Washington, D.C., and Baltimore and used heavily on a daily basis by both commuters and other travelers alike. The other two corridors also carry significant traffic levels and are among the most congested urban highways in the country. The following provide more details on the selected corridors and their geographical extent:

- I-95 between Capital Beltway (I-495) and Baltimore Beltway (I-695)
- MD-295 (Baltimore-Washington Parkway) between D.C. border and Baltimore Beltway (I-695)
- US-29 (Columbia Pike) between Capital Beltway (I-495) and I-70
- Capital Beltway (I-495) between American Legion Bridge (Virginia border) and I-95
- I-270 between Capital Beltway (I-495) and I-70

Figure 10.1 shows the geographic location and extent of the selected corridors on a map. Note that in the map, I-95 is red, MD-295 is green, US-29 is blue, I-495 is gray, and I-270 is yellow. Details on the number of segments in each corridor and their lengths are provided in Appendix E. Also included in Appendix E are further details on each corridor such as average travel times, spatial correlations of travel times along the corridor, and graphs showing the calculated reliability ratio's relationship with trip length and average travel times for each direction of travel as well as morning and afternoon peak periods.

In this chapter, however, the emphasis of reporting (and modeling) is on the first three parallel corridors since they are, by and large, of the same length and virtually are stretched between the same origin and destination pair. However, it should be noted that while I-95 (red) is a four-lane (northbound and southbound) access-controlled freeway facility, MD-295 (green) for the most part is a two-lane (northbound and southbound) access-controlled highway that is under the National Park Service's jurisdiction. Trucks are not allowed on MD-295. Columbia Pike (blue) is mostly a multilane access-controlled highway between I-70 and the newly built MD-200 (Intercounty Connector, or ICC) that runs east-west from I-95 to I-270. However, between the ICC and the Capital Beltway (I-495), US-29 turns into a high-level multilane arterial highway with widely spaced signalized intersections. Therefore, the three selected corridors provide a representative mix of geometry and traffic for further analysis.

Travel time data used as input in this study are provided by INRIX (*32*) through the Vehicle Probe Project (*33*) of the I-95 Corridor Coalition. Data have been pulled and archived since 2009 in the Regional Integrated Transportation Information System (RITIS) (*34*) housed at the Center for Advanced Transportation Technology (CATT) Lab of the University of Maryland. In this study, data archived during calendar year 2011 are used at 1-minute resolution on all segments considered. Analysis is focused on 2-hour peak periods in the morning (7:00 a.m.–9:00 a.m.) and in the afternoon (4:00 p.m.–6:00 p.m.). Path travel times are constructed using segment travel times at their original 1-minute granularity using an instantaneous path travel time estimation algorithm.

Figures 10.2 and 10.3 demonstrate sample histograms of one-time differenced log-travel times on the northbound I-95 corridor and southbound I-270 corridor during AM peak periods, respectively. The histograms show a close match to the hypothesized normal distribution (see Appendix E for details). The chi-square hypothesis testing for all paths formed on all studied corridors at all time periods indicate travel times follow a GBM stochastic process.

Figure 10.4 summarizes the results of analysis on the northbound direction of the three parallel corridors. Each dot on the graphs represents the average of reliability ratios


Source: Map data ©2014 Google.

***Figure 10.1. Corridor examples in Maryland.***

obtained by applying a binary tree for each minute of the corresponding peak period over a given path segment. Therefore, each dot is the average of 120 (2 hours, every minute) binary tree applications for the corresponding set of segments that comprise the same path. Average reliability ratios during AM peak periods are shown on the left graphs, while PM peak reliability ratios are shown on the right graphs. The top graphs depict reliability ratios versus average travel times experienced by travelers. The bottom graphs show the reliability ratios versus trip length. From these graphs it can be seen that reliability ratios are uniformly increasing with both trip length and average travel times. However, the rate of increase diminishes as trips become longer both in space and time. This is due to the fact that over a given corridor as trips become longer by incrementally adding new segments, the trips would inherit both the risks of the currently included segments as well as the risks associated with the newly added segment. The concave form of the reliability ratio curves is mainly due to the fact that, as trip length becomes longer, the risk impact of any newly added segment, while still positive, becomes marginal compared with the rest of the path.

Similarly, Figure 10.5 demonstrates the calculated reliability ratios on the southbound direction of the same three corridors. Both Figure 10.4 and Figure 10.5 indicate more stability in reliability ratio estimates when they are drawn versus average travel times. This fact implies that reliability ratios are strongly correlated with average travel times.

Note that while reported reliability ratios are between zero and one, theoretically there is no real constraint on the maximum possible ratio that can be obtained from applying the proposed method. Example 2 presented in the previous chapter is a case in point. Parameters *a* and *b*, defined earlier in the

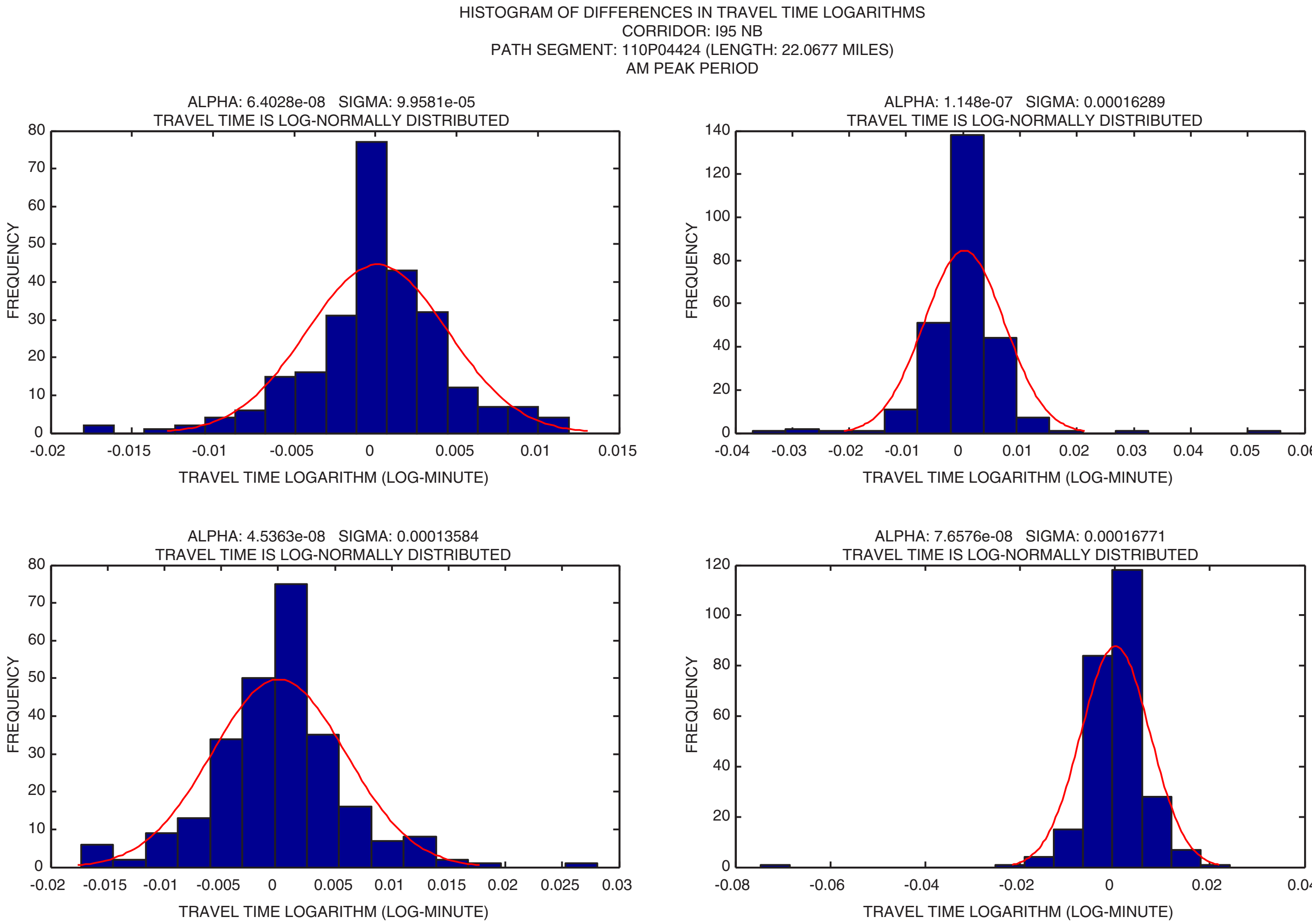


***Figure 10.2. Sample histograms of one-time differenced log-travel times on northbound I-95 corridor during AM peak period.***

payoff characterization section, play an important role in determining the magnitude of reliability ratios.

Figure 10.6 shows the relationship between the 95th percentile travel times and average travel times as is estimated on all incremental paths formed on both directions of the five subject corridors during AM and PM peak periods. The linear relationships between the two measures are clearly visible. However, dispersions around the mean increase as average travel time increases. The linear model fitted to the data by regression displays a high goodness-of-fit measure.

$$\tau_{95} = -0.291 + 1.320 \times E(\tau), (R^2 = 0.97) \quad (10.1)$$

Figure 10.7 shows the ensemble of all estimated reliability ratios along the five studied corridors in both directions and both peak periods. While larger dispersions are visible in the 10 to 20 minutes average travel time range, for both shorter and longer trip times, further convergence in reliability ratios is evident. The general trend is increasing at a diminishing rate. The fitted Gompertz function provides the best estimate of the trend compared with other alternatives. The mean square error reported for this model is just 0.1%.

$$\text{RR} = 1 - \exp\left(17.355 \times \left(\exp\left(-0.004 \times E(\tau)\right) - 1\right)\right), \quad (\text{MSE} = 0.001) \quad (10.2)$$

Figure 10.8 further illustrates scatter of the observed (proposed method) versus model estimated (Equation 10.2) reliability ratios. The linear model fitted to this scattergram indicates a very good fit of the model to the data. The intercept is very close to zero (0.6) and the slope is close to one (0.987) with a strong goodness-of-fit measure (0.98).

$$\widehat{\text{RR}} = 0.006 + 0.987 \times \text{RR}, (R^2 = 0.98) \quad (10.3)$$

In the case of Maryland, a good estimate of the average statewide travel time based on U.S. Census Bureau data during the 5-year period (2006–2010) is approximately 31 minutes

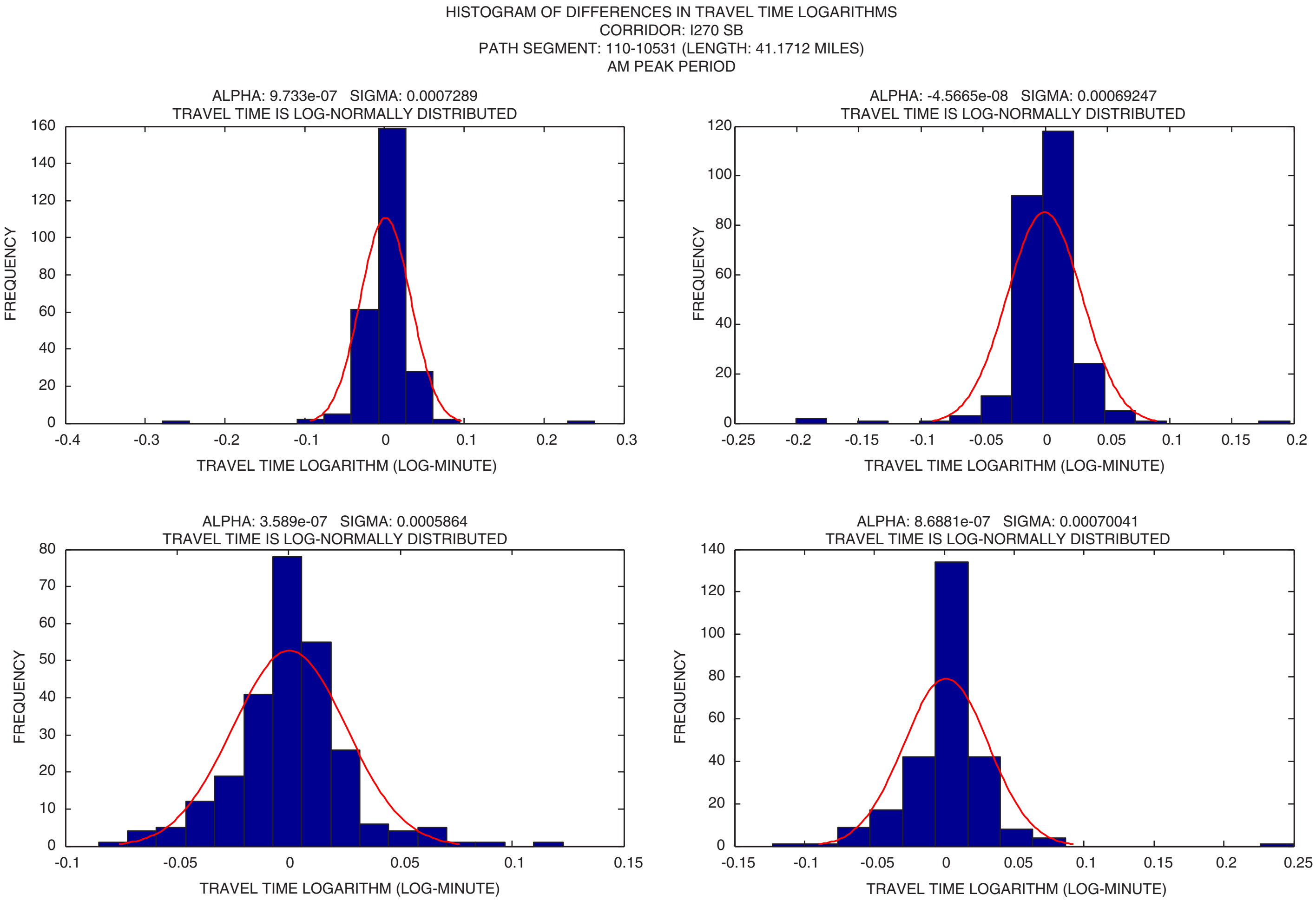


***Figure 10.3. Sample histograms of one-time differenced log-travel times on southbound I-270 corridor during AM peak period.***

(*35*, *36*). Plugging this value into Equation 10.2 would result in a statewide reliability ratio equal to 0.87, which is larger than the current 0.75 value adopted by the state. However, it should be noted that due to the nonlinear (in fact, concavity) form of the model, this is an overestimation. As discussed earlier, in case of the concave function $f(x)$,

$$E[f(x)] < f(E[x]) \tag{10.4}$$

The results of applying the methodology indicate that SHA's use of the current RR of 0.75 is conservative for commute trips. According to the U.S. Census Bureau statistics, average commute trips in Maryland during the 5-year period (2006–2010) has been approximately 31 minutes long (*35*, *36*). However, the corresponding RR value (0.87) is believed to be at the upper range of values for travel time reliability. Further analysis was conducted to justify any decision to increase the current value of travel time reliability.

Maryland Statewide Transportation Model (MSTM) long-term demand and travel time estimates are used in aggregating the results for all origin–destination (O-D) pairs in the state. Based on MSTM, for all trip purposes currently an average reliability ratio value of 0.52 is obtained. This value is expected to increase to 0.55 over the next 15 years until 2030. Similarly, the current average reliability ratio for commute trips in Maryland is estimated to be 0.68 and would remain relatively unchanged until 2030. However, it should be noted that in comparison with Census Bureau estimates, MSTM travel times are on average about 6 minutes smaller. Note that due to bias in self-reporting, Census Bureau estimates tend to be an overestimate. At the same time, it may be argued that MSTM travel times are underestimates caused by spatial aggregations in zone definitions as well as the use of long-term performance functions.

In summary, it can be concluded that during peak hours in congested urban areas, the average reliability ratio ranges between 0.68 and 0.87, derived from MSTM and Census Bureau travel times, respectively. In non-urban areas and at off-peak hours, the average reliability ratio can be taken as 0.52. Therefore, it seems the current value (0.75) is reasonable when reliability of commute travel times during peak hours in congested urban areas is considered.

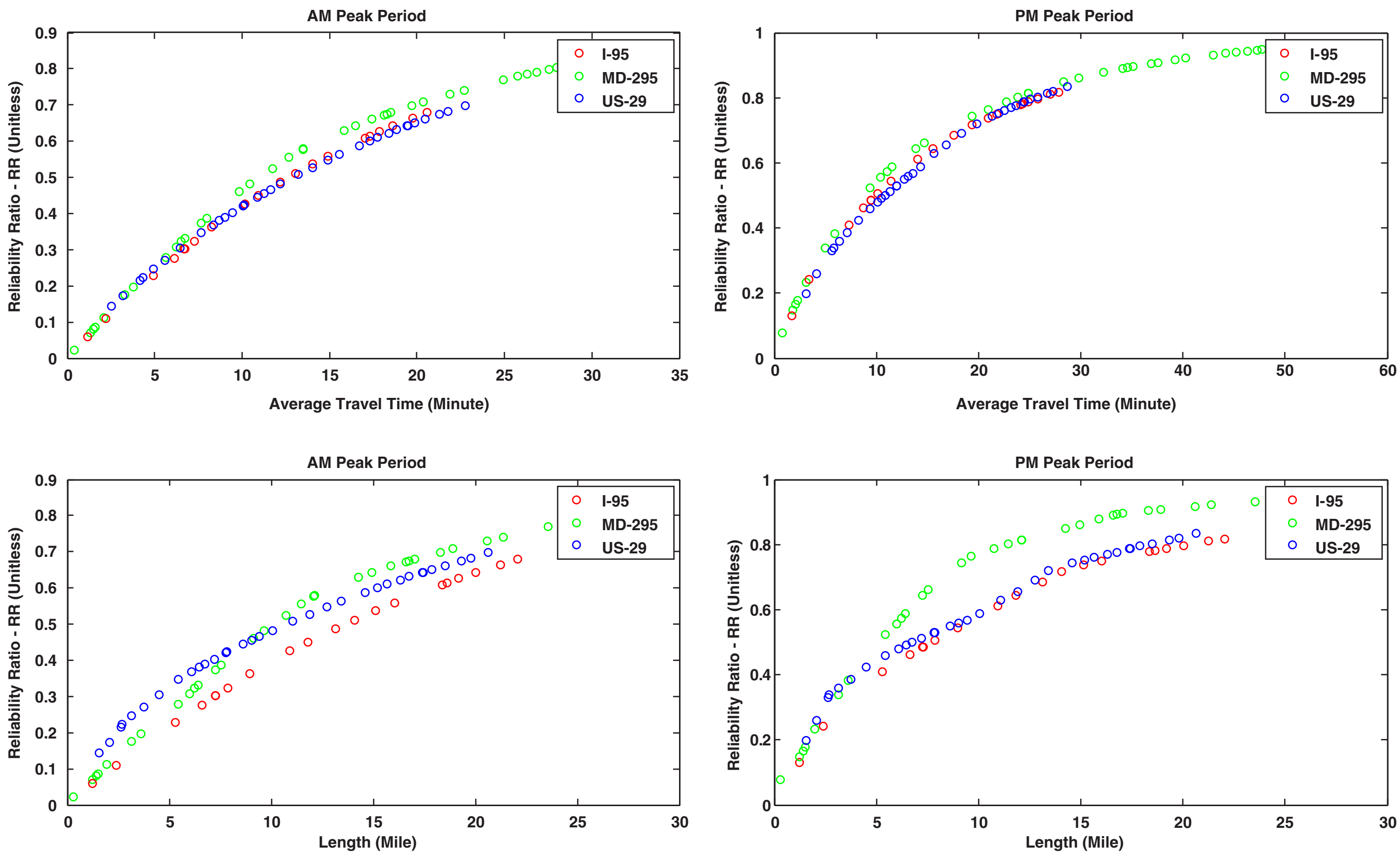


***Figure 10.4. Reliability ratios on the northbound direction of parallel corridors between Capital Beltway and Baltimore Beltway: left, AM peak period; right, PM peak period; top, versus average travel time; and bottom, versus length.***

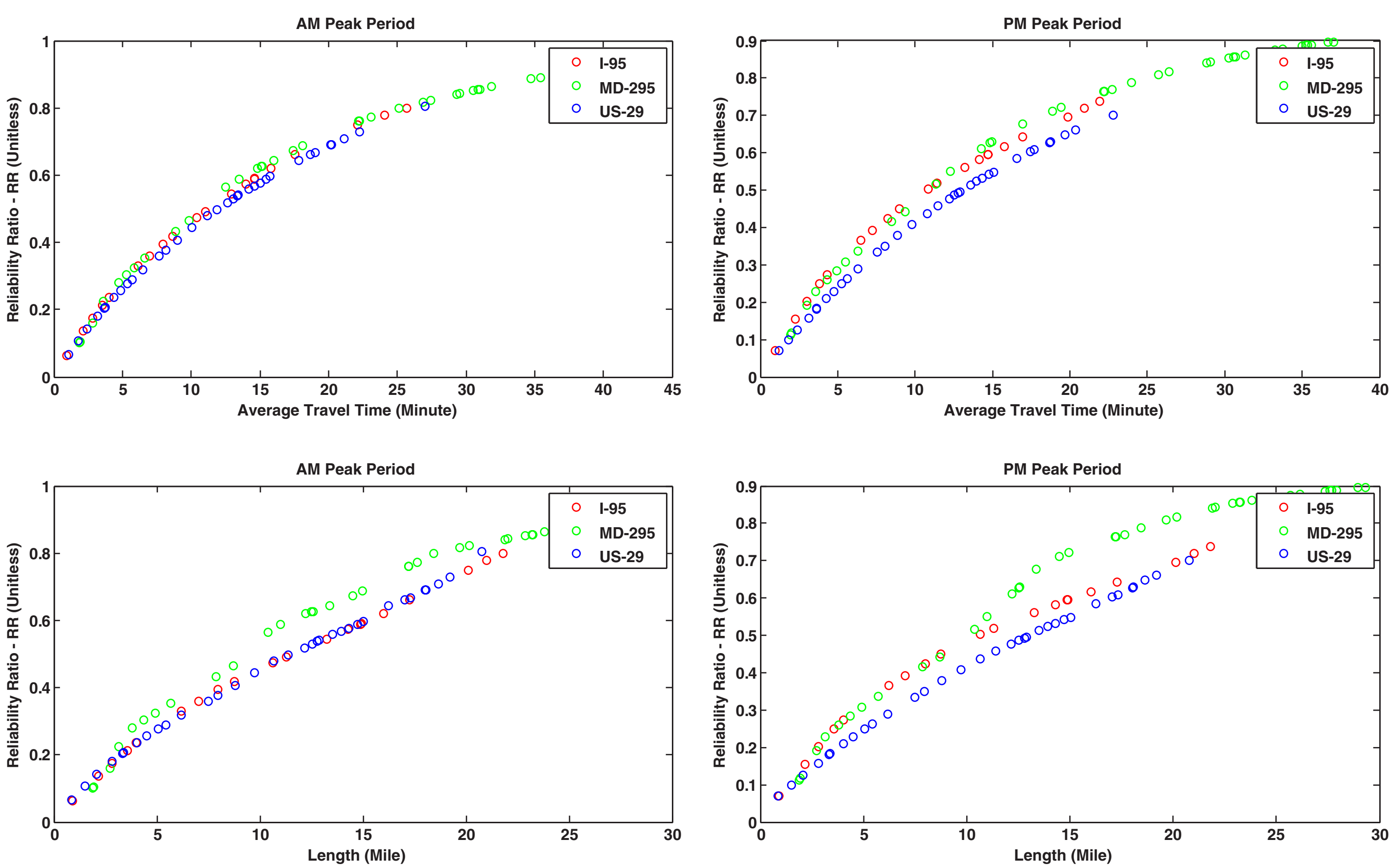


***Figure 10.5. Reliability ratios on the southbound direction of parallel corridors between Capital Beltway and Baltimore Beltway: left, AM peak period; right, PM peak period; top, versus average travel time; bottom, versus length.***

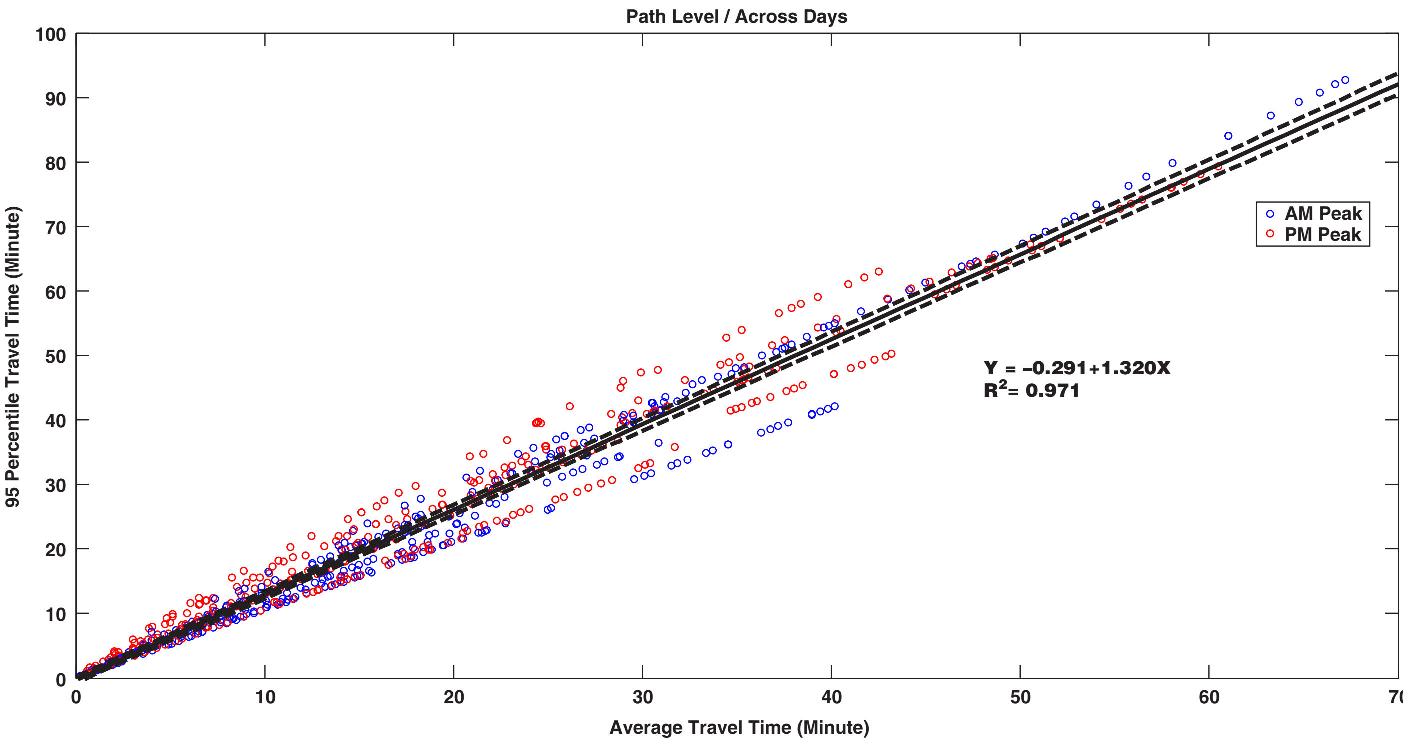


*Figure 10.6. 95th percentile travel time versus average travel time.*

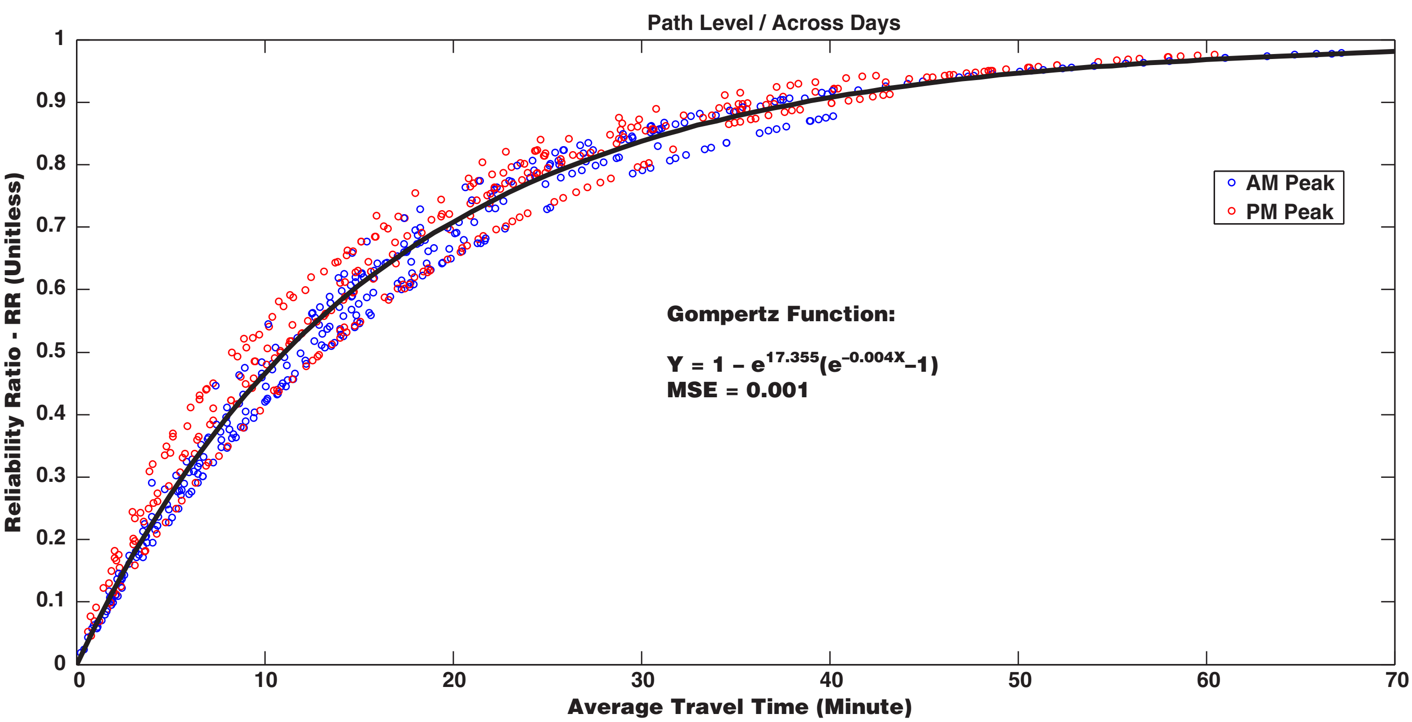


*Figure 10.7. Reliability ratio versus average travel time.*

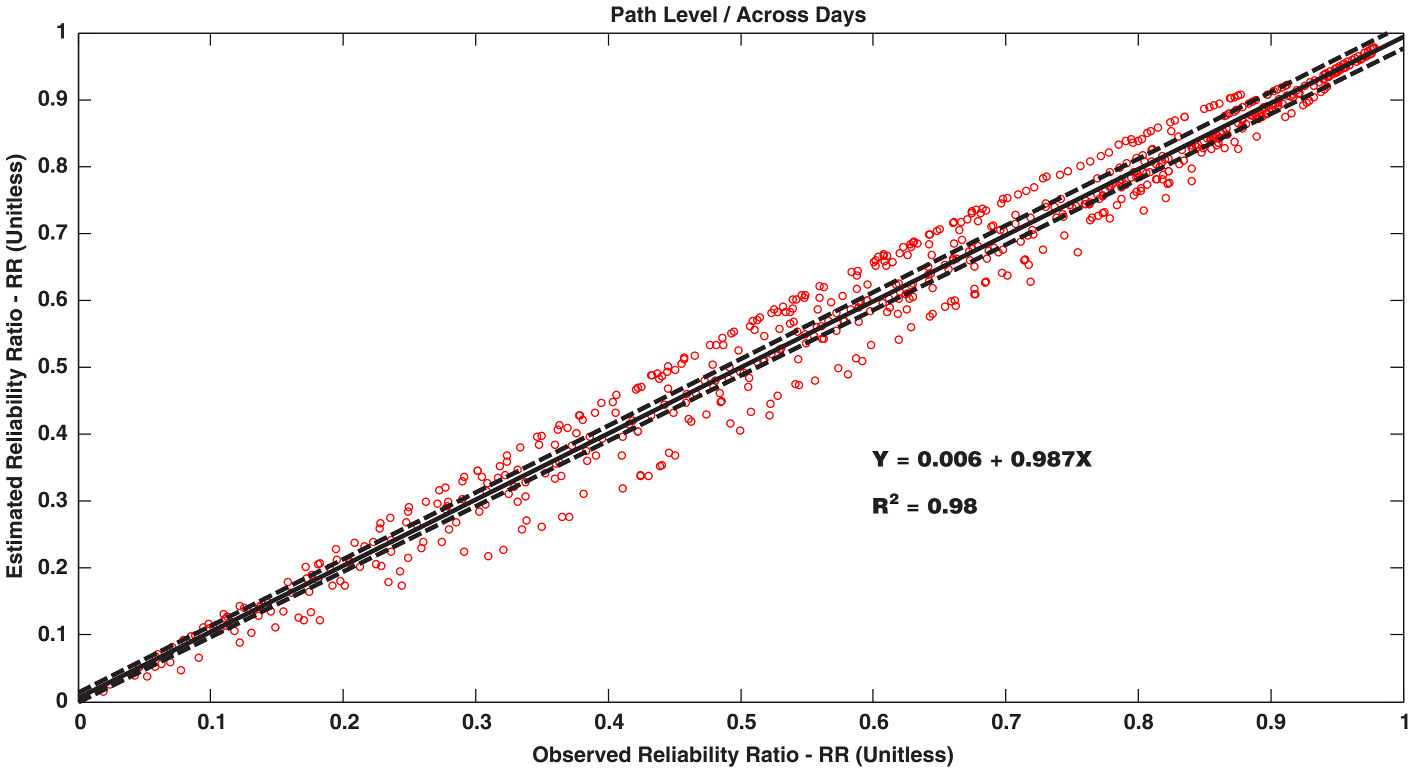


*Figure 10.8. Estimated versus observed reliability ratios.*

# References: Part 2


1. Ben-Akiva, M., and S. Lerman. *Discrete Choice Analysis: Theory and Application to Travel Demand.* The MIT Press, Cambridge, MA, 1985.
2. Manski, C. The Structure of Random Utility Models. *Theory and Decision,* Vol. 8, pp. 229–254, 1977.
3. Carrion, C., and D. Levinson. Value of Travel Time Reliability: A Review of Current Evidence. *Transportation Research Part A: Policy and Practice,* Vol. 46, pp. 720–741, 2012.
4. Cochrane, J. H. *Asset Pricing.* Princeton University Press, Princeton and Oxford, 2005.
5. Sharpe, W. Capital Asset Prices: A Theory of Market Equilibrium Under Conditions of Risk. *Journal of Finance,* Vol. 19, pp. 425–442, 1964.
6. Lintner, J. The Valuation of Risky Assets and the Selection of Risky Investment in Stock Portfolios and Capital Budgets. *Review of Economics and Statistics,* Vol. 47, pp. 13–37, 1965.
7. Ross, S. A. The Arbitrage Theory of Capital Asset Pricing. *Journal of Economic Theory,* Vol. 13, pp. 341–360, 1976.
8. Trigeorgis, L. *Real Options: Managerial Flexibility and Strategy in Resource Allocation.* The MIT Press, Cambridge, MA, 1996.
9. Garvin, M. J., and C. Y. J. Cheah. Valuation Techniques for Infrastructure Investment Decisions. *Construction Management and Economics,* Vol. 22, pp. 373–383, 2004.
10. Pichayapan, P., S. Hino, K. Kishi, and K. Satoh. Real Option Analysis in Evaluation of Expressway Projects Under Uncertainties. *Journal of Eastern Asia Society of Transportation Studies,* Vol. 5, pp. 3015–3030, 2003.
11. Zhao, T., S. K. Sundararajan, and C. L. Tseng. Highway Development Decision Making Under Uncertainty: A Real Options Approach. *Journal of Infrastructure Systems,* Vol. 10(1), pp. 23–32, 2004.
12. Saphores, J.-D. M., and M. G. Boarnet. Uncertainty and the Timing of an Urban Congestion Relief Investment: The No-Land Case. *Journal of Urban Economics,* Vol. 59, pp. 189–208, 2006.
13. Vergara-Alert, C. A Real Option Model for Optimal Investments on Transportation. Presented at 86th Annual Meeting of the Transportation Research Board of the National Academies, Washington, D.C., 2007.
14. Chow, J. Y. J., and A. C. Regan. Real Option Pricing of Network Design Investments. *Transportation Science,* Vol. 45, No. 1, pp. 50–63, 2011.
15. Chow, J. Y. J., and A. C. Regan. Network Based Real Option Models. *Transportation Research Part B: Methodological,* Vol. 45, pp. 682–695, 2011.
16. Longstaff, F. A., and E. S. Schwartz. Valuing American Options by Simulation: A Simple Least-Squares Approach. *The Review of Financial Studies,* Vol. 14, No. 1, pp. 113–147, 2001.
17. Chow, J. Y. J., A. C. Regan, F. Ranaiefar, and D. I. Arkhipov. A Network Option Portfolio Management Framework for Adaptive Transportation Planning. *Transportation Research Part A: Policy and Practice,* Vol. 45, pp. 765–778, 2011.
18. Friesz, T. L., R. Mookherjee, and T. Yao. Securitizing Congestion: The Congestion Call Option. *Transportation Research Part B: Methodological,* Vol. 42, pp. 407–437, 2008.
19. Puget Sound Regional Council. Benefit-Cost Analysis: General Methods and Approach, July 2009 (Updated March 2010). http://www.psrc.org/assets/2127/BCA_Methods_Report_Mar2010update.pdf
20. Kittelson & Associates, Inc. *SHRP 2 S2-L11-RR: Evaluating Alternative Operations Strategies to Improve Travel Time Reliability.* Transportation Research Board of the National Academies, Washington, D.C., 2013. http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2prepubL11.pdf
21. Kittelson & Associates, Inc. *SHRP 2 S2-L17-RR: Guidebook: Placing a Value on Travel Time Reliability.* Transportation Research Board of the National Academies, Washington, D.C., 2013.
22. Guo, F., Q. Li, and H. Rakha. Multi-State Travel Time Reliability Models with Skewed Component Distribution. In *Transportation Research Record. 2315,* TRB, National Research Council, Washington, D.C., pp. 47–53, 2012.
23. Vickrey, W. S. Congestion Theory and Transport Investment. *American Economic Review, Papers and Proceedings,* Vol. 59(2), pp. 251–260, 1969.
24. Small, K. The Scheduling of Consumer Activities: Work Trips. *American Economic Review,* Vol. 72, pp. 467–479, 1982.
25. Noland, R., and K. Small. Travel Time Uncertainty Departure Time Choice and the Cost of Morning Commutes. In *Transportation Research Record 1493,* pp. 150–158, 1995.
26. Fosgerau, M., and A. Karlstrom. The Value of Reliability. *Transportation Research Part B: Methodological,* Vol. 44, pp. 38–49, 2010.
27. Small, K. Valuation of Travel Time. *Economics of Transportation,* Vol. 1, pp. 2–14, 2012.
28. Bates, J., J. Polak, P. Jones, and A. Cook. The Valuation of Reliability for Personal Travel. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 37 (2–3), pp. 191–229, 2001.
29. Small, K., and E. T. Verhoef. *The Economics of Urban Transportation.* Routledge, London and New York, 2007.
30. Lomax, T. J., S. M. Turner, and R. Margiotta. Monitoring Urban Roadways in 2001: Examining Reliability and Mobility with Archived Data. Report No. FHWA-OP-03-041, Washington, D.C., 2003.

31. U.S. Department of Transportation. *The Value of Travel Time: Departmental Guidance for Conducting Economic Evaluations.* Washington, D.C., 1997.
32. INRIX (Driving Intelligence). www.inrix.com
33. I-95 Corridor Coalition. Vehicle Probe Project. http://goo.gl/cFHEd9
34. Center for Advanced Transportation Technology Laboratory at the University of Maryland, College Park. http://www.cattlab.umd.edu/?portfolio=ritis
35. U.S. Department of Transportation, Research and Innovative Technology Administration (RITA). *State Transportation Statistics.* Washington, D.C., 2013. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/state_transportation_statistics/state_transportation_statistics_2013/index.html/chapter4/table4_1
36. IndexMundi. http://www.indexmundi.com/facts/united-states/quick-facts/maryland/average-commute-time#map. Accessed 2013.
37. Pearle, P., B. Collett, K. Bart, D. Bilderback, D. Newman, and S. Samuels. What Brown Saw and You Can Too. *American Journal of Physics,* Vol. 78(12), 2010. http://physerver.hamilton.edu/Research/Brownian/index.html
38. Einstein, A. On the Movement of Small Particles Suspended in Stationary Liquids Required by the Molecular-Kinetic Theory of Heat. *Annalen der Physik,* Vol. 17, pp. 549–560, 1905.
39. Wiener, N. The Average of an Analytical Functional and the Brownian Movement. *Proceedings of the National Academy of Sciences of the United States of America,* Vol. 7, No. 10, pp. 294–298, 1921.
40. Bachelier, L. Theorie de la Speculation. *Annales Scientifiques de l'Ecole Normal Superieur,* 3e serie, tome 17, pp. 21–86, 1900.
41. Feller, W. *An Introduction to Probability Theory and Its Applications.* John Wiley & Sons, 1950.
42. Dixit, A. K., and R. S. Pindyck. *Investment Under Uncertainty.* Princeton University Press, N.J., 1994.
43. Yeon, J., L. Elefteriadou, and S. Lawphongpanich. Travel Time Estimation on a Freeway using Discrete Time Markov Chains. *Transportation Research Part B: Methodological,* Vol. 42, pp. 325–338, 2008.
44. Pearson, K. The Problem of the Random Walk. *Nature,* Vol. 72, No. 1867, p. 342, 1905.
45. Aitchison, J., and J. A. C. Brown. *The Lognormal Distribution.* Cambridge University Press, London, 1957.

APPENDIX D

# Background on Stochastic Processes

## Brownian Motion and Wiener Process

Robert Brown (1773–1858) was an early nineteenth-century botanist who studied the jittery motion of small grains of pollen in water under a microscope. He then observed the same motion in particles of inorganic matter suspended in water, which enabled him to rule out the existence of a biologic cause for the observed motion (*37*). Thus, he concluded the motions have to have a physical source.

In 1905 Albert Einstein published a paper (*38*) that showed movements of small particles in liquids can be explained by the thermal motions of liquid molecules and their kinetic impacts on the floating particles. While he mentions Brownian motion in this work, he states he does not have enough data to give a verdict on whether the type of motions that he discusses here are the same as the ones that were reported by Brown. This work made it possible to determine the real size of atoms and molecules.

Norbert Wiener, a renowned mathematician and MIT professor (1894–1964), built on earlier work and argued that Einstein's assumptions on the independence of an interval from previous intervals and applicability of Stokes' law are approximations. He showed that mean square displacement in a given direction of a spherical particle in a fluid over any given time interval $\Delta t$ is effectively proportionate to the length of the time interval $\left(\overline{\Delta^2 z} \cong c\Delta t\right)$. In other words, he showed that floating particles displacement is proportional to the square root of the time interval over which displacement is taking place (*39*).

Louis Bachelier (1870–1946), a French mathematician and the so-called founder of mathematical finance, as part of his PhD dissertation (*40*) modeled a stochastic process that today is known as Brownian motion. Interestingly, his dissertation was published in 1900 (5 years before Einstein's work). Some even have suggested that what is known today as Brownian motion should be renamed as the Wiener-Bachelier process (*41*). Bachelier's work later inspired A. Kolmogorov to develop the formal foundations of Markov processes.

A Wiener process (also called a Brownian motion) is a continuous-time stochastic process with three important properties (*42*). First, it is a Markov process, which means that the probability distribution for all future values of the process depends only on its current value, and is unaffected by past values of the process or by any other current information. In other words, Markov property suggests that process is memoryless, which in the case of process $\{z\}$ can be written as the following:

$$P\left(z(s+\Delta t)\middle|z(s), z(s-\Delta t), \ldots, z(0)\right)$$
$$= P\left(z(s+\Delta t)\middle|z(s)\right), \forall s, \Delta t > 0 \qquad \text{(D.1)}$$

In the field of transportation, travel time variations over time are usually assumed to resemble a Markov process (*43*).

Second, the Wiener process has independent increments. This property suggests that the probability distribution for the change in the process over any time interval is independent of any other (non-overlapping) time interval. Third, changes in the process ($\Delta z$) over any finite interval of time ($\Delta t$) are normally distributed with a variance that increases linearly with the time interval.

$$z(s+\Delta t) - z(s) = \Delta z \sim N(0, \Delta t) \qquad \text{(D.2)}$$

Thus, any increments in a Wiener process over a finite time interval are linearly related to the square root of the time step.

$$\Delta z = \varepsilon_t \sqrt{\Delta t}, \varepsilon_t \sim N(0,1) \qquad \text{(D.3)}$$

where $\varepsilon_t$ is a standard normal random variable. And, in the limit as the time interval is reduced, the process is defined as

$$dz = \varepsilon_t \sqrt{dt}, \varepsilon_t \sim N(0,1) \qquad \text{(D.4)}$$

It should be noted that the latter property holds for every time step size. For instance, over a time step $T$ (equal in size to $n$ smaller time steps),

$$T = n\Delta t \tag{D.5}$$

The process increment may be written as the sum of increments in all smaller time intervals:

$$z(s+T) - z(s) = \sum_{i=1}^{n} \varepsilon_i \sqrt{\Delta t} = \sqrt{\Delta t} \sum_{i=1}^{n} \varepsilon_i \tag{D.6}$$

In the above equation, it should be noted that the sum in the rightmost term is, in fact, the sum of $n$ independent and identically distributed (iid) standard normal random variables. Using central limit theorem (CLT), it can be shown that this sum is normally distributed with mean zero and variance $n$. Thus, the process increment is also normally distributed with mean zero and variance equal to the time interval $T$,

$$z(s+T) - z(s) \sim N\left(0, \left(\sqrt{T}\right)^2\right) \tag{D.7}$$

Therefore, in the limit as $T$ increases ($T \rightarrow \infty$), the expected increment is zero while the variance of increment will increase unboundedly.

Also, note that the Wiener process has no time derivatives in a conventional sense:

$$\Delta z / \Delta t = \varepsilon_t / \sqrt{\Delta t} \tag{D.8}$$

and, as time interval $\Delta t$ is reduced,

$$\lim_{\Delta t \rightarrow 0} \left(\frac{\Delta z}{\Delta t}\right) = \frac{dz}{dt} = \infty \tag{D.9}$$

## Brownian Motion with Drift

The Wiener process can be easily extended to represent more complex processes. The following process is called "Brownian motion with drift":

$$dx = a\,dt + \sigma dz \tag{D.10}$$

where

$dz$ is the increment of a Wiener process as defined above;
$a$ is the drift parameter; and
$\sigma$ is the standard deviation parameter.

From the previous discussion it is straightforward to see that over a time interval $\Delta t$, the process increment is normally distributed:

$$\Delta x \sim N(a\Delta t, \sigma^2 \Delta t) \tag{D.11}$$

This leads to the following difference equation in discrete time to represent the trajectory of process $x$:

$$x_{n+1} = x_n + a\Delta t + \sigma\sqrt{\Delta t}\,\varepsilon_n \tag{D.12}$$

## Random Walk Representation of Brownian Motion

From the preceding discussion, it is clear that a continuous Wiener process can be simply described in terms of a random walk. A random walk is a succession of random steps (*44*). In the case of one-dimensional movements, a simple metaphor is the position of a person on a ladder (Figure D.1), where at

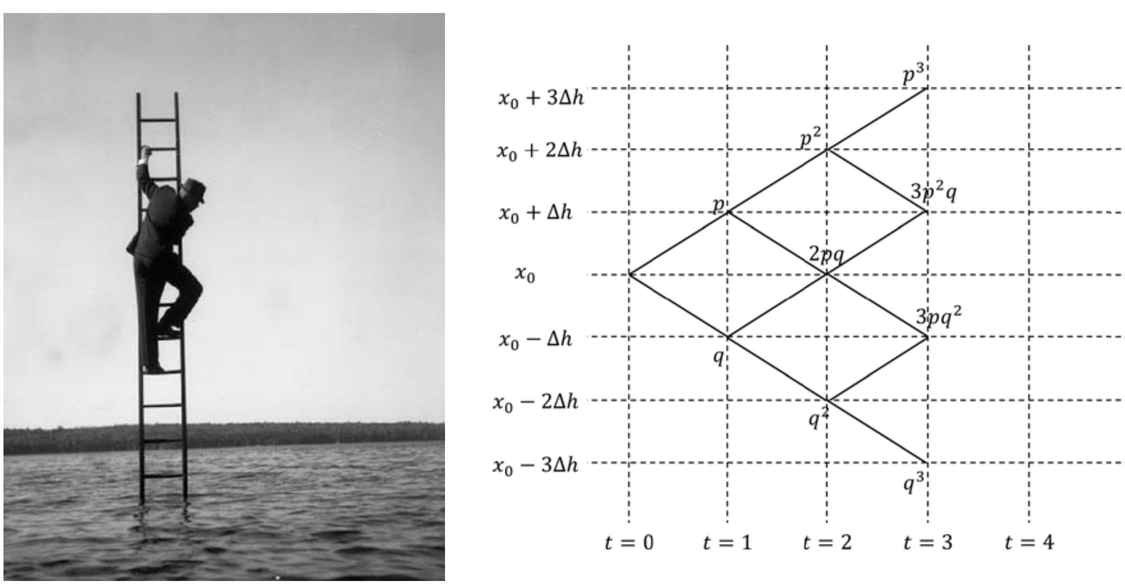


***Figure D.1. Random walk representation of Wiener process in one dimension: left, man on the ladder metaphor; right, Manhattan grid metaphor.***

the end of each time interval that person takes a step up or down from his current position with certain probabilities.

Expanding on the same idea, and starting from the man's initial position on the ladder ($x_0$), over time we can draw his possible positions on a rectangular grid. In the grid shown in Figure D.1, the *x*-axis represents time steps and the *y*-axis represents the man's position on the ladder. In this grid representation, the uniform step size on the ladder is denoted by $\Delta h$ and the probability of taking one step up is denoted by *p*, while the probability of taking one step down is denoted by *q*. It should be noted that $p + q = 1$. By connecting his possible positions from one time step to the next, a tree form emerges that has its root at his initial position ($x_0$) at the initial time ($t = 0$), and which spreads (diffuses) in both directions as time goes by. The probability of the man being at any of the nodes on this tree depends on the number of paths along the tree (starting from his initial position) he can take to reach that particular node and the number of up and down steps he has to take along each path. Since the man's decisions at each time step are independent of other time steps, the up and down probabilities can be multiplied to obtain the path probability. At each time step, probability of the man being positioned at any of the possible steps on the ladder is determined by a binomial distribution.

$$P(X = x_0 \pm k\Delta h) = \binom{n}{k} p^k q^{n-k},\ p + q = 1; \quad k = n, n-2, \ldots \tag{D.13}$$

$$E[\Delta x] = (p - q)\Delta h \tag{D.14}$$

$$E\left[(\Delta x)^2\right] = (p + q)\Delta h = \Delta h \tag{D.15}$$

$$\begin{aligned} V[\Delta x] &= E\left[(\Delta x)^2\right] - (E[\Delta x])^2 \\ &= \left[1 - (p - q)^2\right](\Delta h)^2 = 4pq(\Delta h)^2 \end{aligned} \tag{D.16}$$

$$T = n\Delta t \tag{D.17}$$

$$[x(T) - x(0)] \sim \text{Binomial} \tag{D.18}$$

$$E[x(T) - x(0)] = n(p - q)\Delta h = T(p - q)(\Delta h/\Delta t) \tag{D.19}$$

$$V[x(T) - x(0)] = n\left[1 - (p - q)^2\right](\Delta h)^2 = 4pqT\left((\Delta h)^2/\Delta t\right) \tag{D.20}$$

We would like the mean and variance of $[x(T) - x(0)]$ to remain unchanged and to be independent of the particular choice of probabilities (*p, q*), and discretization stencil ($\Delta h$, $\Delta t$). To achieve this goal, it is common to set

$$\Delta h = \sigma\sqrt{\Delta t} \tag{D.21}$$

$$p = \frac{1}{2}\left[1 + \frac{a}{\sigma}\sqrt{\Delta t}\right] \tag{D.22}$$

$$q = 1 - p = \frac{1}{2}\left[1 - \frac{a}{\sigma}\sqrt{\Delta t}\right] \tag{D.23}$$

Thus,

$$p - q = \frac{a}{\sigma}\sqrt{\Delta t} = \frac{a}{\sigma^2}\Delta h \tag{D.24}$$

$$pq = \frac{1}{4}\left[1 - \frac{a^2}{\sigma^2}\Delta t\right] \tag{D.25}$$

Then,

$$E[x(T) - x(0)] = T\left(\frac{a}{\sigma^2}\Delta h\right)(\Delta h/\Delta t) = aT \tag{D.26}$$

$$V[x(T) - x(0)] = \left[1 - \frac{a^2}{\sigma^2}\Delta t\right]T\left((\Delta h)^2/\Delta t\right) = \left[1 - \frac{a^2}{\sigma^2}\Delta t\right]T\sigma^2 \tag{D.27}$$

In the limit, as time steps become smaller the mean and variance of the displacement from initial position as described by random walk will be equal to the following:

$$E[x(T) - x(0)] = aT \tag{D.28}$$

$$V[x(T) - x(0)] = \sigma^2 T \tag{D.29}$$

Note that both mean and variance of the random walk in the limit are independent of the adopted discretization stencil. Besides, they are equal to the mean and variance of the process described by Brownian motion with drift.

## Generalized Brownian Motion (Ito Processes)

The Wiener process provides a very basic and natural description of variability in many physical and social phenomena. As such it can be further generalized to model a wide range of stochastic processes:

$$dx = a(x,t)dt + b(x,t)dz \tag{D.30}$$

where

*dz* is the increment of a Wiener process;
$a(x,t)$ is the expected instantaneous drift rate; and
$b(x,t)$ is the instantaneous standard deviation rate.

Note that in the general definition the drift and standard deviation coefficients are both known (nonrandom) functions of the current state and time. The generalized continuous-time stochastic process $x(t)$ presented here is called an Ito process.

The mean and variance of the increments of this process are, respectively,

$$E(dx) = a(x,t)dt \tag{D.31}$$

$$V[dx] = E\left[(dx)^2\right] - (E[dx])^2 = b^2(x,t)dt \tag{D.32}$$

Note that in calculating the variance, terms in which $dt$ orders are higher than one are dropped:

$$(dx)^2 = a^2(x,t)(dt)^2 + b^2(x,t)dt + 2a(x,t)b(x,t)(dt)^{3/2} \tag{D.33}$$

$$E\left[(dx)^2\right] = b^2(x,t)dt \tag{D.34}$$

## Ito's Lemma

It was discussed earlier that the Ito process is continuous in time, but it is not necessarily smooth enough to be differentiable. However, in most practical cases we deal with functions of Ito processes. Therefore, computationally it is desirable to be able to differentiate or to integrate such functions. This possibility is provided through use of the so-called Ito's lemma.

Ito's lemma is very similar to a Taylor series expansion of a function around a given point. Suppose that $x(t)$ follows an Ito process, and consider a function $F(x,t)$ that is at least twice differentiable in $x$ and once in $t$. According to the rules of calculus, the total differential of this function can be written as

$$dF = \frac{\partial F}{\partial t}dt + \frac{\partial F}{\partial x}dx + \frac{1}{2}\frac{\partial^2 F}{\partial x^2}(dx)^2 + \frac{1}{6}\frac{\partial^3 F}{\partial x^3}(dx)^3 + \cdots \tag{D.35}$$

Substituting Equation D.30 for $dx$ and dropping higher-order terms would result in the following expression for the total differential of the function:

$$dF = \left[\frac{\partial F}{\partial t} + a(x,t)\frac{\partial F}{\partial x} + \frac{1}{2}b^2(x,t)\frac{\partial^2 F}{\partial x^2}\right]dt + b(x,t)\frac{\partial F}{\partial x}dz \tag{D.36}$$

which illustrates that any function of an Ito process is itself an Ito process. See the following example.

$$F(x,t) = \log x;\ a(x,t) = ax;\ b(x,t) = \sigma x$$

Note that in this case, $\frac{\partial F}{\partial t} = 0,\ \frac{\partial F}{\partial x} = \frac{1}{x},\ \frac{\partial^2 F}{\partial x^2} = \frac{-1}{x^2}$

Substituting these partial derivatives in Equation D.36 would result in

$$dF = \left(a - \frac{1}{2}\sigma^2\right)dt + \sigma dz \tag{D.37}$$

This suggests that over a time interval $\Delta t$, the change in log $x$ is normally distributed with mean $\left(a - \frac{1}{2}\sigma^2\right)\Delta t$ and variance $\sigma^2\,\Delta t$. So, in this case compared with the instantaneous rate of change in process $x$ $\left(\text{that is, } \frac{dx}{x}\right)$, log $x$ is expected to change over time with a rate less than half its variance.

Note that log $x$ is a strictly concave function of $x$, $\left(\frac{\partial^2 F}{\partial x^2} < 0\right)$, so applying Jensen's inequality, it can be shown that with $x$ uncertain, the expected value of log $x$ changes by less than the logarithm of the expected value of $x$. In the case of two random points $x_1$ and $x_2$, the following illustrates the above reasoning:

$$w \log x_1 + (1-w)\log x_2 \le \log\left(wx_1 + (1-w)x_2\right) \tag{D.38}$$

$$E[\log x] \le \log(E[x]) \tag{D.39}$$

These equations can be easily extended to the general case where an infinite number of points on the $x$ axis (random variable) are considered.

## Geometric Brownian Motion

A very important special case of Ito processes is the geometric Brownian motion with drift (GBM), in which $a(x,t) = ax$, and $b(x,t) = \sigma x$, where $a$ and $\sigma$ are constants. The following is the expression for a GBM process:

$$dx = axdt + \sigma xdz \tag{D.40}$$

Note that $dx/x = d\log x = dF$, therefore GBM suggests that natural logarithm of random variable $x$ is following a simple Brownian motion with drift stochastic process, and therefore $F = \log x$ is normally distributed. In other words, recalling the Ito's lemma and the example previously discussed, the GBM process suggests that random variable $x$ is lognormally distributed and can be expressed using the following Brownian motion with drift process:

$$dF = \left(a - \frac{1}{2}\sigma^2\right)dt + \sigma dz \tag{D.41}$$

$$E[\Delta F] = \left(a - \frac{1}{2}\sigma^2\right)\Delta t \tag{D.42}$$

$$V[\Delta F] = \sigma^2 \Delta t \tag{D.43}$$

As for $x$ itself, starting from initial time $t_0$, its expected position at time $t$ is given by (*45*)

$$E[x(t)] = x(t_0)\exp\{a(t - t_0)\} \tag{D.44}$$

And the variance of $x(t)$ is given by

$$V[x(t)] = x^2(t_0)\exp\{2a(t-t_0)\}(\exp\{\sigma^2(t-t_0)\}-1) \quad \text{(D.45)}$$

## Random Walk Representation of Geometric Brownian Motion

As shown previously, a simple Brownian motion process can be represented by a random walk. In this section we show that geometric Brownian motion can also be represented by a random walk. This argument is supported by the fact when a random variable follows GBM process, its natural logarithm would follow a simple Brownian motion. Building on this fact we can write the size of increments in terms of the logarithm of $x$ at three neighboring points as

$$\log x_{n+1} - \log x_n = \Delta h \quad \text{(D.46)}$$

$$\log x_n - \log x_{n-1} = \Delta h \quad \text{(D.47)}$$

Thus, starting from the middle point ($x_n$) it is possible to find the other two neighboring points based on the following equations:

$$x_{n+1} = x_n \exp(\Delta h) = u x_n \quad \text{(D.48)}$$

$$x_{n-1} = x_n \exp(-\Delta h) = d x_n \quad \text{(D.49)}$$

where $u$ and $d$ are multiplicative factors by which $x_n$ gets transformed into the upper and lower neighboring points, respectively. Also, note that $u$ and $d$ are inverse of each other.

$$u = 1/d \quad \text{(D.50)}$$

As before, setting the step size $\Delta h$ equal to the standard deviation of increments in the logarithm of random variable $x$ would lead to the following expressions for $u$ and $d$ factors:

$$\Delta h = \sigma\sqrt{\Delta t} \quad \text{(D.51)}$$

$$u = \exp\left[\sigma\sqrt{\Delta t}\right] \quad \text{(D.52)}$$

$$d = \exp\left[-\sigma\sqrt{\Delta t}\right] \quad \text{(D.53)}$$

Similarly, probabilities of taking a step up or a step down in the random walk is given by

$$p = \frac{1}{2}\left[1 + \left(\left(a - \frac{\sigma^2}{2}\right)\Big/\sigma\right)\sqrt{\Delta t}\right] \quad \text{(D.54)}$$

$$q = 1 - p = \frac{1}{2}\left[1 - \left(\left(a - \frac{\sigma^2}{2}\right)\Big/\sigma\right)\sqrt{\Delta t}\right] \quad \text{(D.55)}$$

Thus,

$$p - q = \left(\left(a - \frac{\sigma^2}{2}\right)\Big/\sigma\right)\sqrt{\Delta t} = \left(\left(a - \frac{\sigma^2}{2}\right)\Big/\sigma^2\right)\Delta h \quad \text{(D.56)}$$

$$pq = \frac{1}{4}\left[1 - \left(\left(a - \frac{\sigma^2}{2}\right)\Big/\sigma\right)^2 \Delta t\right] \quad \text{(D.57)}$$

Then,

$$E[x(T) - x(0)] = T\left(\left(a - \frac{\sigma^2}{2}\right)\Big/\sigma^2\right)(\Delta h)^2/\Delta t = \left(a - \frac{\sigma^2}{2}\right)T \quad \text{(D.58)}$$

$$V[x(T) - x(0)] = \left[1 - \left(\left(a - \frac{\sigma^2}{2}\right)\Big/\sigma\right)^2 \Delta t\right] T\left((\Delta h)^2/\Delta t\right)$$

$$= \left[1 - \left(\left(a - \frac{\sigma^2}{2}\right)\Big/\sigma\right)^2 \Delta t\right] T\sigma^2 \quad \text{(D.59)}$$

In the limit, as time steps become smaller the mean and variance of the displacement from initial position as described by random walk will be equal to the following:

$$E[x(T) - x(0)] = \left(a - \frac{\sigma^2}{2}\right)T \quad \text{(D.60)}$$

$$V[x(T) - x(0)] = \sigma^2 T \quad \text{(D.61)}$$

Note that both mean and variance of the random walk in the limit are independent of the adopted discretization stencil. Besides, they are equal to the mean and variance of the stochastic process described as geometric Brownian motion with drift.

## GBM Calibration and Hypothesis Testing

Given a series $\{x\}$ of random variables sampled at $\Delta t$ time intervals, the following hypothesis test needs to be performed in order to determine whether $\{x\}$ is a GBM process:

$$\begin{cases} H_0: x \text{ is a GBM process} \\ H_1: x \text{ is not a GBM process} \end{cases} \quad \text{(D.62)}$$

Recall that a GBM process is equivalent to asserting that increments in the natural logarithm of $\{x\}$ are normally distributed with specific mean and variance,

$$(\log x_{n+1} - \log x_n) \sim N\left(\left(a - \frac{\sigma^2}{2}\right)\Delta t, \sigma^2 \Delta t\right) \quad \text{(D.63)}$$

Therefore, the first step to test the hypothesis is to form a series of increments of the natural logarithm of the series $\{x\}$:

$$y_n = \log x_n - \log x_{n-1} = \log\left(x_n / x_{n-1}\right), n = 1, 2, \ldots \quad \text{(D.64)}$$

The second step is to verify whether series $\{y\}$ is normally distributed. For this purpose, initially we need to estimate the mean and variance of the transformed series $\{y\}$:

$$E[y] = \left(\hat{a} - \frac{1}{2}\hat{\sigma}^2\right)\Delta t \quad \text{(D.65)}$$

$$V[y] = \hat{\sigma}^2 \Delta t \quad \text{(D.66)}$$

Solving for the instantaneous trend and standard deviation of the GBM process, the following estimates of the pair of parameters are obtained:

$$\hat{\sigma} = \sqrt{\frac{V[y]}{\Delta t}} = \frac{SD[y]}{\sqrt{\Delta t}} \quad \text{(D.67)}$$

$$\hat{a} = \frac{2E[y] + V[y]}{2\Delta t} \quad \text{(D.68)}$$

Now, the original hypothesis test can be written in an equivalent form:

$$\begin{cases} H_0: y \sim N\left(\left(\hat{a} - \frac{1}{2}\hat{\sigma}^2\right)\Delta t, \hat{\sigma}^2 \Delta t\right) \\ H_1: \textit{Otherwise} \end{cases} \quad \text{(D.69)}$$

This hypothesis can be tested using a chi-square goodness-of-fit test. The chi-square test statistic is of the form

$$\chi^2 = \sum_{i=1}^{N} (O_i - E_i)^2 / E_i \quad \text{(D.70)}$$

where

$N$ is the number of bins;

$O_i$ are the observed counts; and

$E_i$ are the expected counts based on the hypothesized distribution.

Usually bins are defined in such a way that the expected count in a given bin based on the hypothesized distribution does not fall below 5. As a result, bin sizes do not have to be uniform. In most cases the square root of the length of the series $\{y\}$ is a good starting point for the number of bins ($N$) to be considered in performing the hypothesis test.

The test statistic has an approximate chi-square distribution when the counts are sufficiently large. At a given significance level ($a$), if the test statistic is smaller than the corresponding value of the chi-square distribution ($\chi^2 \leq \chi^2_a$), then the chi-square test does not reject the null hypothesis at the $a$ significance level. Otherwise, the null hypothesis is rejected.

Note that if the null hypothesis is not rejected it is not automatically accepted. In fact, failure to reject the null hypothesis at a significance level merely means that evidence against the hypothesis is not overwhelming. It does not mean that there is evidence in favor of the hypothesis. Therefore, when the null hypothesis is not rejected, other evidence, including the nature of the process and visuals such as graphs and histograms, may be sought to confirm the nature of the process that data are hypothesized to follow.

APPENDIX E

# Details on Corridor Examples

This appendix provides further details on corridor examples presented in this report. For each corridor, a comprehensive description of standard traffic message channel (TMC) segments included therein is provided (Tables E.1 through E.11). Average travel times over the length of each corridor in AM and PM peak periods are presented (Figures E.1, E.4, E.7, E.10, E.13, E.16, E.19, E.22, E.25, and E.28). These graphs can be used conveniently to identify the peak direction of flow in each corridor and also to identify mileposts along the corridor in which congestion builds up frequently during each peak period.

Also, to illustrate the correlations between travel time at different segments along the corridor, travel time correlation heat maps are presented (Figures E.2, E.5, E.8, E.11, E.14, E.17, E.20, E.23, E.26, and E.29). Note that in the heat maps, red colors represent higher correlations while blue colors represent lower correlations. Naturally, segments next to each other are more likely to show a simultaneous increase or decrease in travel time (travel speed). The correlation heat maps can be used as a tool to segment the corridors into subcorridors with homogeneous traffic patterns during AM and PM peak periods.

Finally, for each corridor and peak period combination, reliability ratios on paths formed by incrementally adding single TMC segments are reported for every minute of the 2-hour-long peak period Figures E.3, E.6, E.9, E.12, E.15, E.18, E.21, E.24, E.27, and E.30. This is potentially very informative as the information makes it abundantly clear which TMC segments and exactly at what times would contribute the most to the corridor unreliability. Also, average reliability ratios of incremental subpaths in each peak period are depicted versus the length of the corresponding corridor subpaths.

*Table E.1. Summary Details of Corridors Reported*

| Highway | Direction | Number of TMC Segments | Length (mi) |
|---|---|---|---|
| I-95 | Northbound | 20 | 22.1 |
| I-95 | Southbound | 20 | 21.8 |
| I-270 | Northbound | 49 | 41.0 |
| I-270 | Southbound | 49 | 41.2 |
| I-495 | Clockwise (inner loop) | 23 | 15.0 |
| I-495 | Counterclockwise (outer loop) | 23 | 16.0 |
| MD-295 | Northbound | 38 | 29.5 |
| MD-295 | Southbound | 38 | 29.3 |
| US-29 | Northbound | 34 | 20.7 |
| US-29 | Southbound | 34 | 20.8 |

*Table E.2. TMC Segment Definitions on Northbound I-95 Corridor*

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110+04261 | I-95 | MD-212/Exit 29 | PRINCE GEORGE'S | NORTHBOUND | 1.238947 |
| 110P04261 | I-95 | MD-212/Exit 29 | PRINCE GEORGE'S | NORTHBOUND | 1.147974 |
| 110+04262 | I-95 | MD-198/Exit 33 | PRINCE GEORGE'S | NORTHBOUND | 2.922258 |
| 110P04262 | I-95 | MD-198/Exit 33 | PRINCE GEORGE'S | NORTHBOUND | 1.319046 |
| 110+04263 | I-95 | Howard/Prince George's Co Line (Laurel) (West) | PRINCE GEORGE'S | NORTHBOUND | 0.641658 |
| 110+04417 | I-95 | Howard/Prince George's Co Line (Laurel) (East) | HOWARD | NORTHBOUND | 0.011807 |
| 110+04418 | I-95 | MD-216/Exit 35 | HOWARD | NORTHBOUND | 0.597041 |
| 110P04418 | I-95 | MD-216/Exit 35 | HOWARD | NORTHBOUND | 1.088444 |
| 110+04419 | I-95 | MD-32/Exit 38 | HOWARD | NORTHBOUND | 1.966358 |
| 110P04419 | I-95 | MD-32/Exit 38 | HOWARD | NORTHBOUND | 0.870892 |
| 110+04420 | I-95 | MD-175/Exit 41 | HOWARD | NORTHBOUND | 1.339863 |
| 110P04420 | I-95 | MD-175/Exit 41 | HOWARD | NORTHBOUND | 0.923773 |
| 110+04421 | I-95 | MD-100/Exit 43 | HOWARD | NORTHBOUND | 1.053211 |
| 110P04421 | I-95 | MD-100/Exit 43 | HOWARD | NORTHBOUND | 0.912837 |
| 110+04422 | I-95 | I-895/Exit 46 | HOWARD | NORTHBOUND | 2.336029 |
| 110P04422 | I-95 | I-895/Exit 46 | HOWARD | NORTHBOUND | 0.247628 |
| 110+04423 | I-95 | I-195/MD-166/Exit 47 | BALTIMORE | NORTHBOUND | 0.583805 |
| 110P04423 | I-95 | I-195/MD-166/Exit 47 | BALTIMORE | NORTHBOUND | 0.830501 |
| 110+04424 | I-95 | I-695/Exit 49 | BALTIMORE | NORTHBOUND | 1.223226 |
| 110P04424 | I-95 | I-695/Exit 49 | BALTIMORE | NORTHBOUND | 0.812418 |

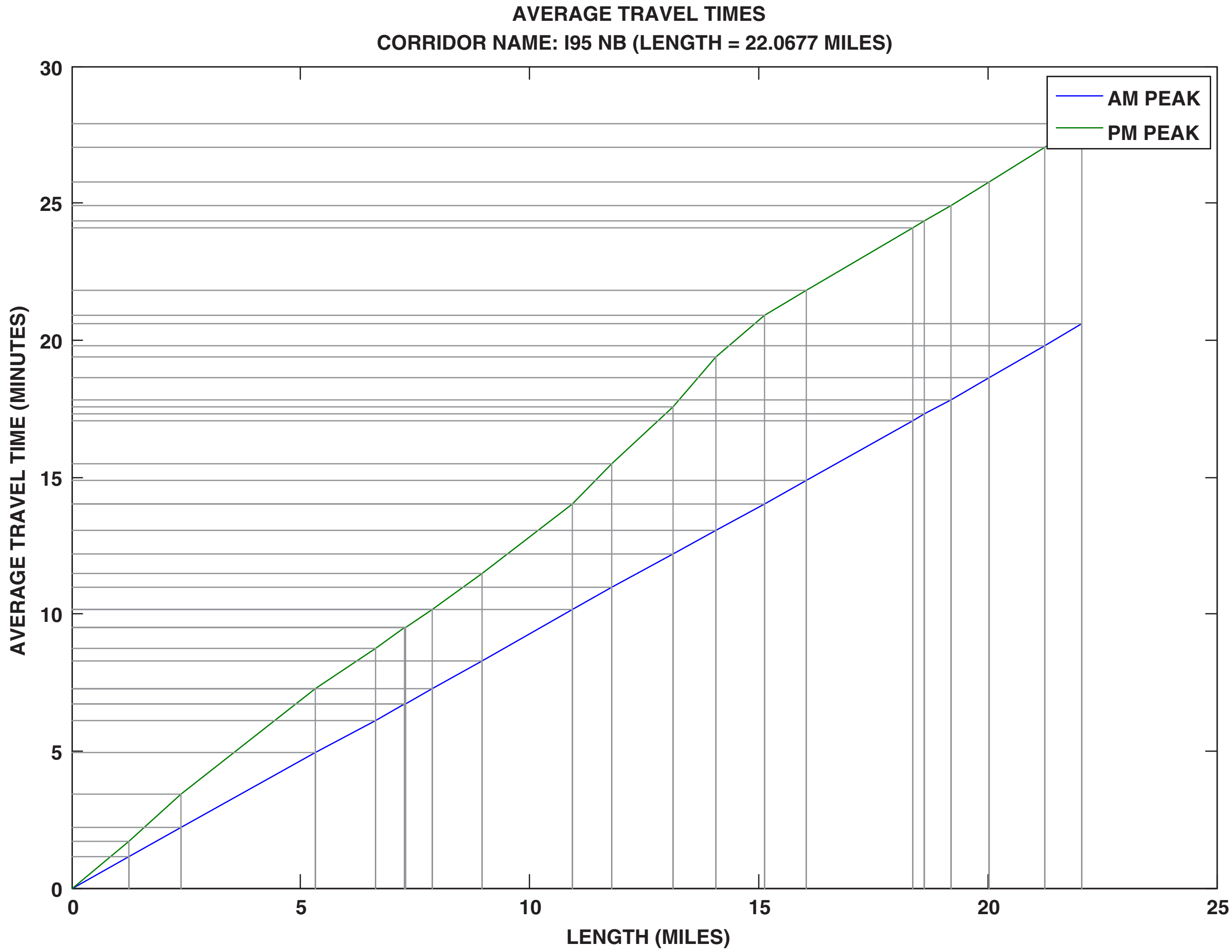


*Figure E.1. Average travel time versus length on northbound I-95 corridor.*

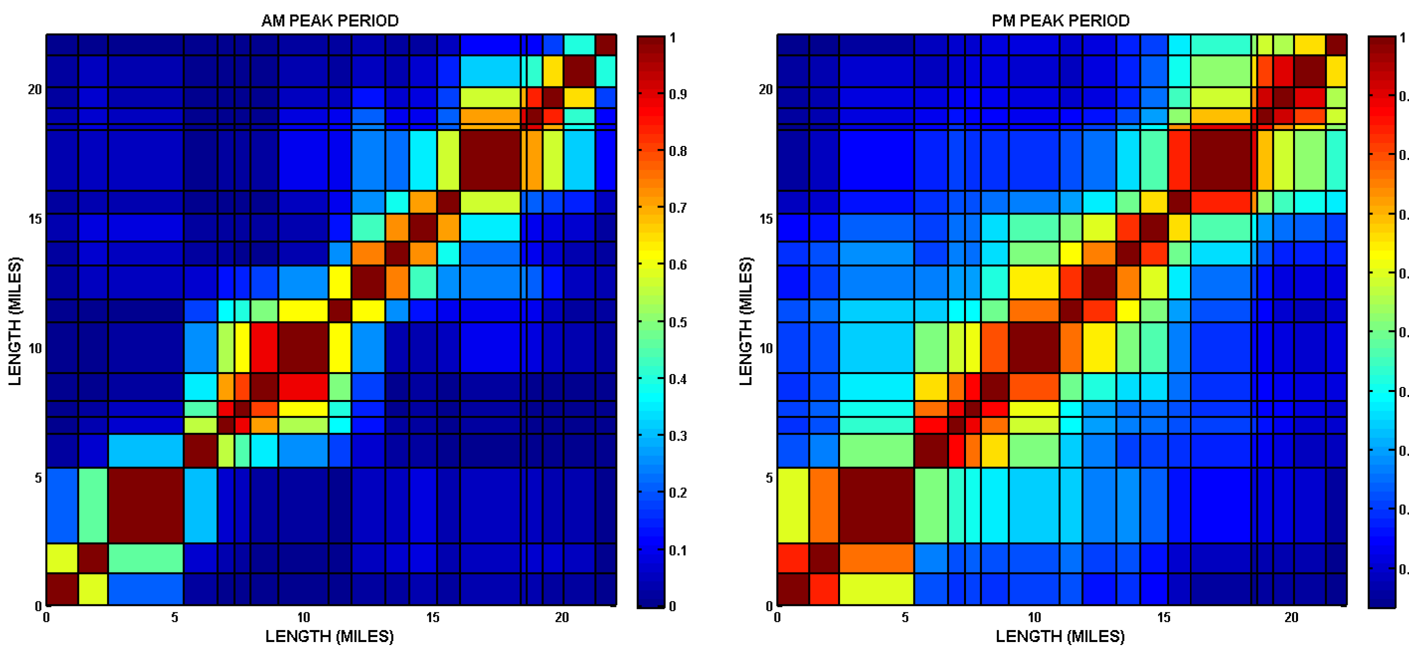


*Figure E.2. Travel time correlations on northbound I-95 corridor: left, AM peak period; right, PM peak period.*

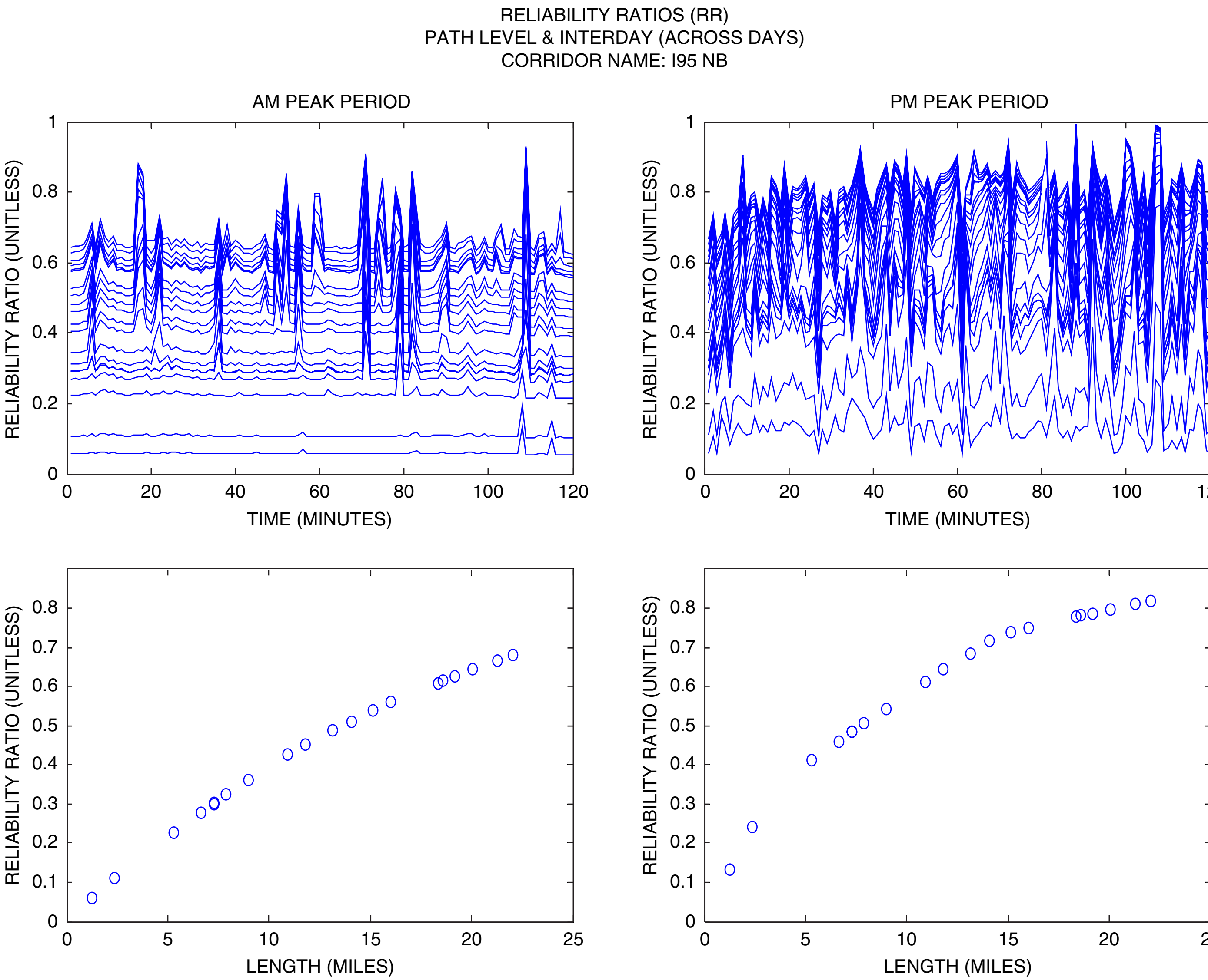


***Figure E.3. Analysis results on northbound I-95 corridor: left, AM peak period; right, PM peak period; top, reliability ratio over time; and bottom, average reliability ratio versus length.***

*Table E.3. TMC Segment Definitions on Southbound I-95 Corridor*

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110N04424 | I-95 | I-695/Exit 49 | BALTIMORE | SOUTHBOUND | 0.924333 |
| 110-04423 | I-95 | I-195/MD-166/Exit 47 | BALTIMORE | SOUTHBOUND | 1.249014 |
| 110N04423 | I-95 | I-195/MD-166/Exit 47 | BALTIMORE | SOUTHBOUND | 0.663158 |
| 110-04422 | I-95 | I-895/Exit 46 | HOWARD | SOUTHBOUND | 0.727535 |
| 110N04422 | I-95 | I-895/Exit 46 | HOWARD | SOUTHBOUND | 0.449024 |
| 110-04421 | I-95 | MD-100/Exit 43 | HOWARD | SOUTHBOUND | 2.200626 |
| 110N04421 | I-95 | MD-100/Exit 43 | HOWARD | SOUTHBOUND | 0.804464 |
| 110-04420 | I-95 | MD-175/Exit 41 | HOWARD | SOUTHBOUND | 0.971372 |
| 110N04420 | I-95 | MD-175/Exit 41 | HOWARD | SOUTHBOUND | 0.754504 |
| 110-04419 | I-95 | MD-32/Exit 38 | HOWARD | SOUTHBOUND | 1.902851 |
| 110N04419 | I-95 | MD-32/Exit 38 | HOWARD | SOUTHBOUND | 0.658187 |
| 110-04418 | I-95 | MD-216/Exit 35 | HOWARD | SOUTHBOUND | 1.950575 |
| 110N04418 | I-95 | MD-216/Exit 35 | HOWARD | SOUTHBOUND | 1.035439 |
| 110-04417 | I-95 | Howard/Prince George's Co Line (Laurel) (East) | HOWARD | SOUTHBOUND | 0.582314 |
| 110-04263 | I-95 | Howard/Prince George's Co Line (Laurel) (West) | PRINCE GEORGE'S | SOUTHBOUND | 0.040764 |
| 110-04262 | I-95 | MD-198/Exit 33 | PRINCE GEORGE'S | SOUTHBOUND | 1.090495 |
| 110N04262 | I-95 | MD-198/Exit 33 | PRINCE GEORGE'S | SOUTHBOUND | 1.261877 |
| 110-04261 | I-95 | MD-212/Exit 29 | PRINCE GEORGE'S | SOUTHBOUND | 2.855954 |
| 110N04261 | I-95 | MD-212/Exit 29 | PRINCE GEORGE'S | SOUTHBOUND | 0.888291 |
| 110-04260 | I-95 | I-495/Exit 27-25 | PRINCE GEORGE'S | SOUTHBOUND | 0.786195 |

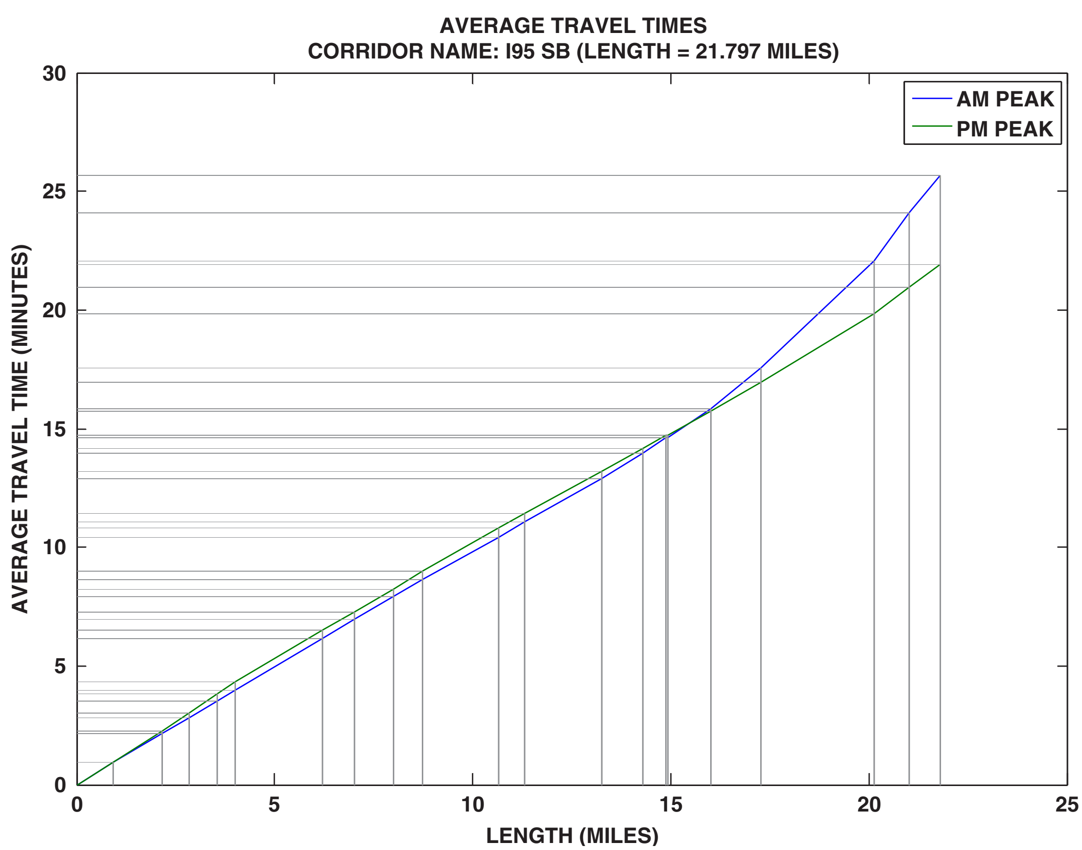


*Figure E.4. Average travel time versus length on southbound I-95 corridor.*

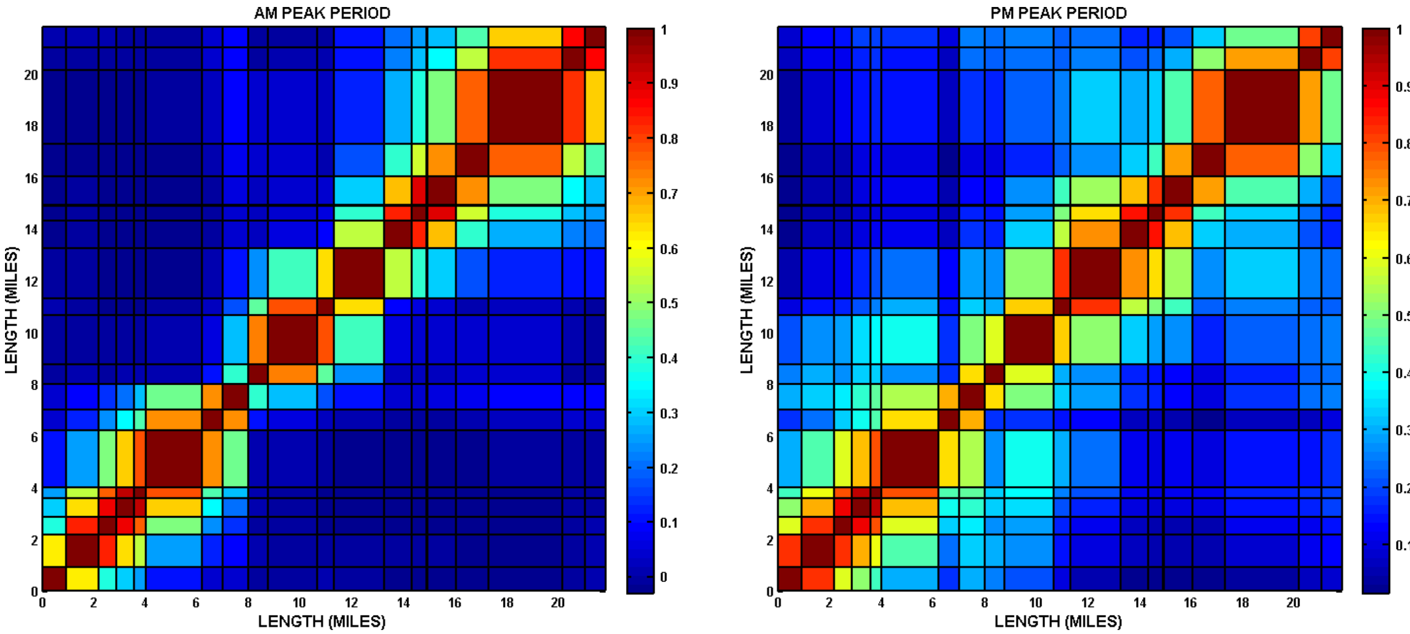


***Figure E.5. Travel time correlations on southbound I-95 corridor: left, AM peak period; right, PM peak period.***

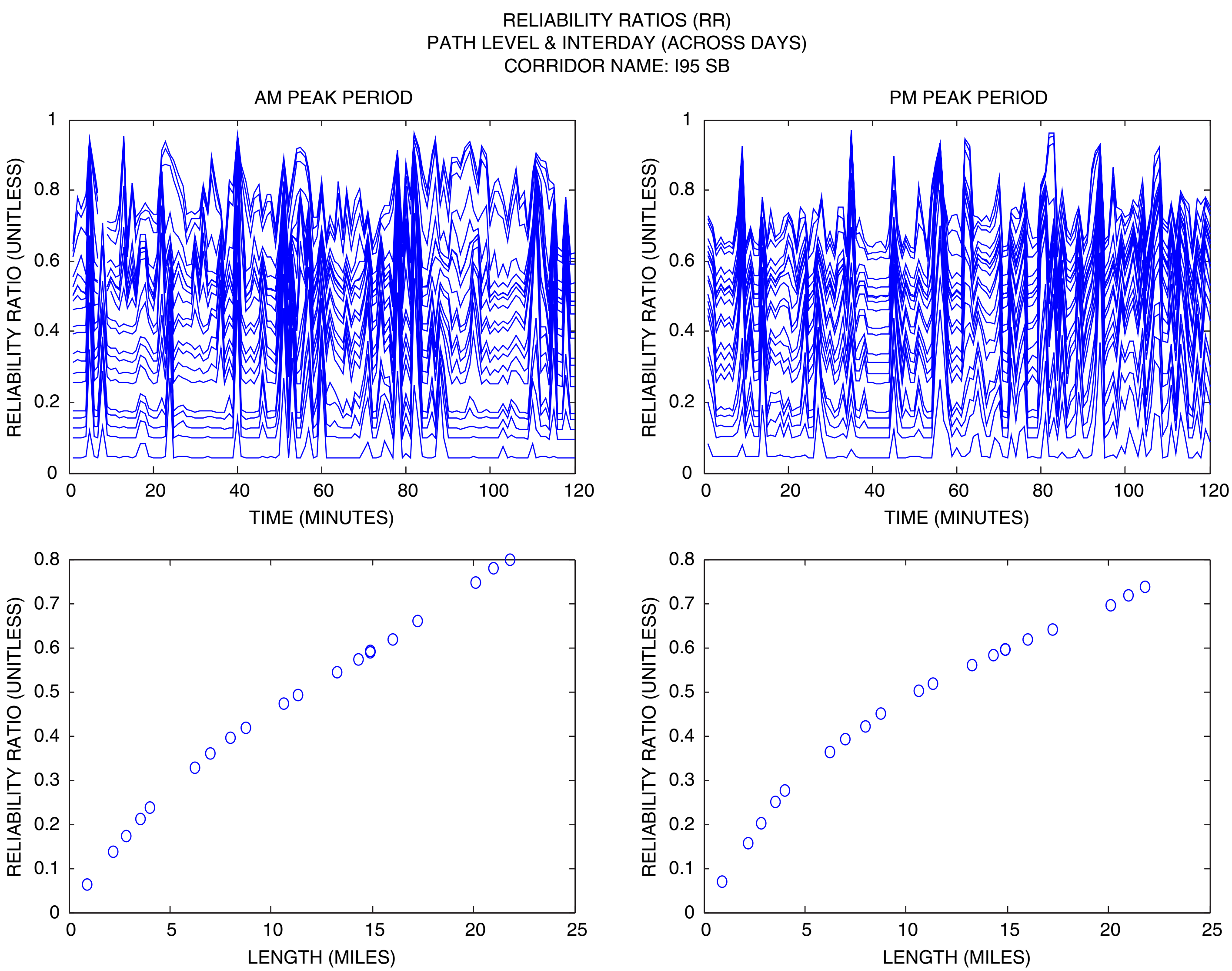


***Figure E.6. Analysis results on southbound I-95 corridor: left, AM peak period; right, PM peak period; top, reliability ratio over time; and bottom, average reliability ratio versus length.***

*Table E.4. TMC Segment Definitions on Northbound I-270 Corridor*

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110+04103 | I-270 | MD-187/Old Georgetown Rd/Exit 1 | MONTGOMERY | NORTHBOUND | 1.080863 |
| 110P04103 | I-270 | MD-187/Old Georgetown Rd/Exit 1 | MONTGOMERY | NORTHBOUND | 0.767429 |
| 110+04104 | I-270 | I-270 | MONTGOMERY | NORTHBOUND | 0.08246 |
| 110P04104 | I-270 | I-270 | MONTGOMERY | NORTHBOUND | 0.519118 |
| 110+04105 | I-270 | Montrose Rd/Exit 4 | MONTGOMERY | NORTHBOUND | 1.138529 |
| 110P04105 | I-270 | Montrose Rd/Exit 4 | MONTGOMERY | NORTHBOUND | 0.523902 |
| 110+04106 | I-270 | MD-189/Falls Rd/Exit 5 | MONTGOMERY | NORTHBOUND | 0.956645 |
| 110P04106 | I-270 | MD-189/Falls Rd/Exit 5 | MONTGOMERY | NORTHBOUND | 0.3496 |
| 110+04107 | I-270 | MD-28/Montgomery Ave/Exit 6 | MONTGOMERY | NORTHBOUND | 0.530738 |
| 110P04107 | I-270 | MD-28/Montgomery Ave/Exit 6 | MONTGOMERY | NORTHBOUND | 0.44281 |
| 110+04108 | I-270 | Shady Grove Rd/Exit 8 | MONTGOMERY | NORTHBOUND | 1.468555 |
| 110P04108 | I-270 | Shady Grove Rd/Exit 8 | MONTGOMERY | NORTHBOUND | 0.490285 |
| 110+04109 | I-270 | I-370/Sam Eig Hwy/Exit 9 | MONTGOMERY | NORTHBOUND | 0.393781 |
| 110P04109 | I-270 | I-370/Sam Eig Hwy/Exit 9 | MONTGOMERY | NORTHBOUND | 0.574049 |
| 110+04110 | I-270 | MD-117/Exit 10 | MONTGOMERY | NORTHBOUND | 1.228819 |
| 110P04110 | I-270 | MD-117/Exit 10 | MONTGOMERY | NORTHBOUND | 0.019512 |
| 110+04111 | I-270 | MD-124/Quince Orchard Rd/Exit 11 | MONTGOMERY | NORTHBOUND | 0.419818 |
| 110P04111 | I-270 | MD-124/Quince Orchard Rd/Exit 11 | MONTGOMERY | NORTHBOUND | 0.403289 |
| 110+04112 | I-270 | Middlebrook Rd/Exit 13 | MONTGOMERY | NORTHBOUND | 2.074047 |
| 110P04112 | I-270 | Middlebrook Rd/Exit 13 | MONTGOMERY | NORTHBOUND | 0.212208 |
| 110+04113 | I-270 | MD-118/Exit 15 | MONTGOMERY | NORTHBOUND | 0.477794 |
| 110P04113 | I-270 | MD-118/Exit 15 | MONTGOMERY | NORTHBOUND | 0.648307 |
| 110+04114 | I-270 | Father Hurley Blvd/Exit 16 | MONTGOMERY | NORTHBOUND | 0.28137 |
| 110P04114 | I-270 | Father Hurley Blvd/Exit 16 | MONTGOMERY | NORTHBOUND | 0.635444 |
| 110+04115 | I-270 | MD-121 | MONTGOMERY | NORTHBOUND | 2.170053 |
| 110P04115 | I-270 | MD-121 | MONTGOMERY | NORTHBOUND | 0.220597 |
| 110+04116 | I-270 | MD-109/Exit 22 | MONTGOMERY | NORTHBOUND | 3.841557 |
| 110P04116 | I-270 | MD-109/Exit 22 | MONTGOMERY | NORTHBOUND | 0.216185 |
| 110+04117 | I-270 | MD-80/Exit 26 | FREDERICK | NORTHBOUND | 3.499849 |
| 110P04117 | I-270 | MD-80/Exit 26 | FREDERICK | NORTHBOUND | 0.175235 |
| 110+04118 | I-270 | MD-85/Exit 31 | FREDERICK | NORTHBOUND | 4.713754 |
| 110P04118 | I-270 | MD-85/Exit 31 | FREDERICK | NORTHBOUND | 0.526637 |
| 110+04119 | I-270 | I-70/US-40 | FREDERICK | NORTHBOUND | 0.386697 |
| 110P04119 | I-270 | I-70/US-40 | FREDERICK | NORTHBOUND | 1.014187 |
| 110+10532 | I-270 | Montrose Rd | MONTGOMERY | NORTHBOUND | 0.325862 |
| 110P10532 | I-270 | Montrose Rd | MONTGOMERY | NORTHBOUND | 0.523902 |
| 110+10533 | I-270 | MD-189/Great Falls Rd | MONTGOMERY | NORTHBOUND | 0.956645 |
| 110P10533 | I-270 | MD-189/Great Falls Rd | MONTGOMERY | NORTHBOUND | 0.3496 |

*(continued on next page)*

*Table E.4. TMC Segment Definitions on Northbound I-270 Corridor (continued)*

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110+10534 | I-270 | MD-28/W Montgomery Ave | MONTGOMERY | NORTHBOUND | 0.756679 |
| 110P10534 | I-270 | MD-28/W Montgomery Ave | MONTGOMERY | NORTHBOUND | 0.004661 |
| 110+10535 | I-270 | Shady Grove Rd | MONTGOMERY | NORTHBOUND | 1.680763 |
| 110P10535 | I-270 | Shady Grove Rd | MONTGOMERY | NORTHBOUND | 0.490285 |
| 110+10536 | I-270 | I-370 | MONTGOMERY | NORTHBOUND | 0.393781 |
| 110P10536 | I-270 | I-370 | MONTGOMERY | NORTHBOUND | 0.574049 |
| 110+10537 | I-270 | MD-117/W Diamond Ave | MONTGOMERY | NORTHBOUND | 1.228819 |
| 110P10537 | I-270 | MD-117/W Diamond Ave | MONTGOMERY | NORTHBOUND | 0.019512 |
| 110+10538 | I-270 | MD-124/Montgomery Village Ave | MONTGOMERY | NORTHBOUND | 0.419818 |
| 110P10538 | I-270 | MD-124/Montgomery Village Ave | MONTGOMERY | NORTHBOUND | 0.403289 |
| 110+10539 | I-270 | I-270/Washington National Pike | MONTGOMERY | NORTHBOUND | 0.35339 |

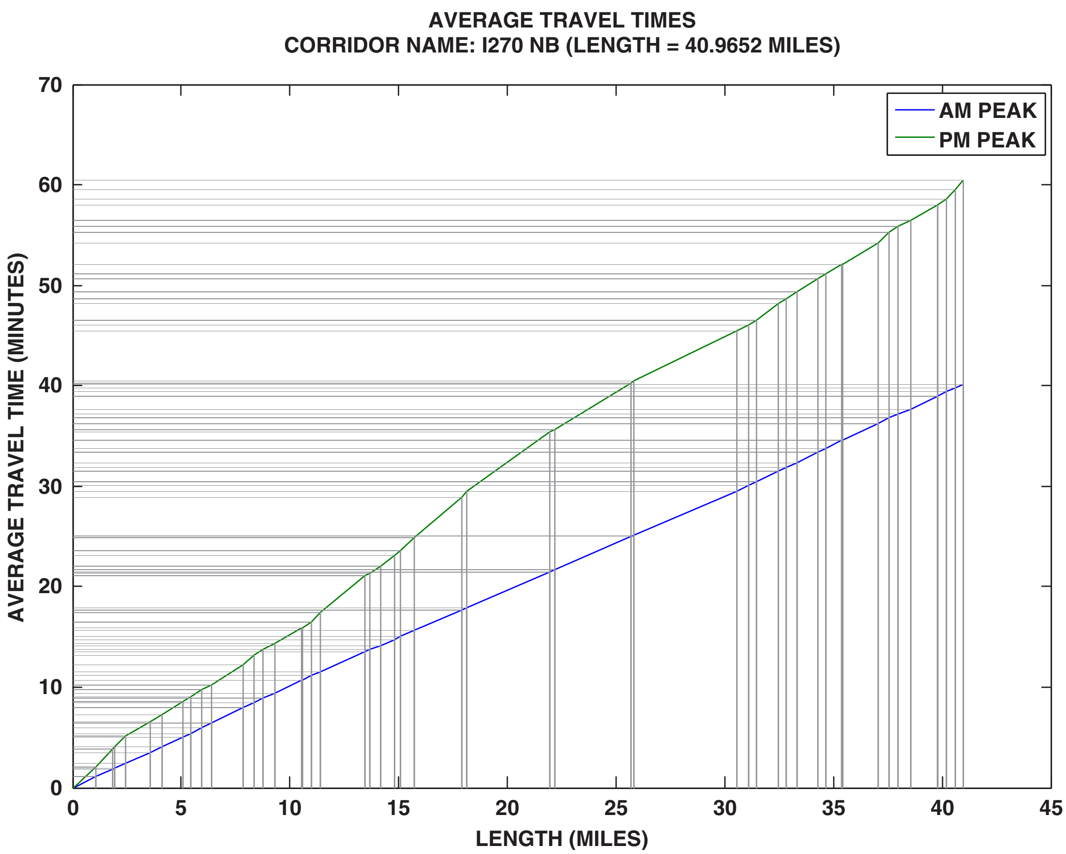


*Figure E.7. Average travel time versus length on northbound I-270 corridor.*

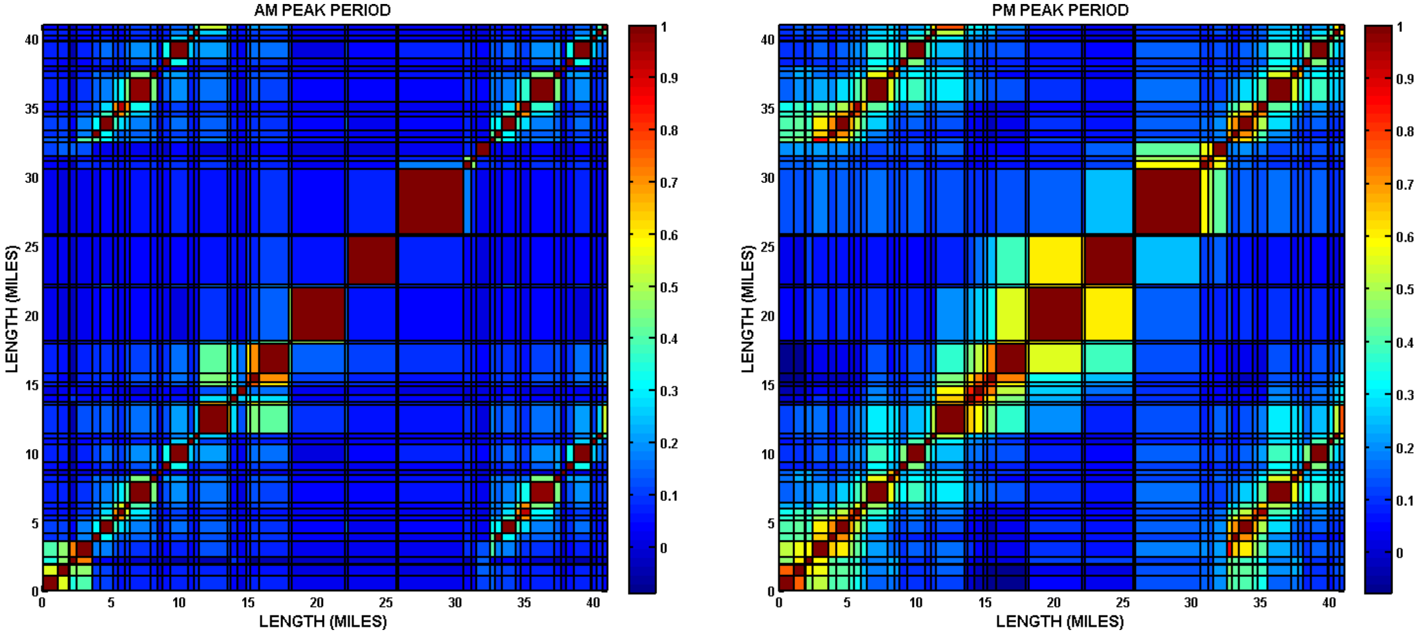


***Figure E.8. Travel time correlations on northbound I-270 corridor: left, AM peak period; right, PM peak period.***

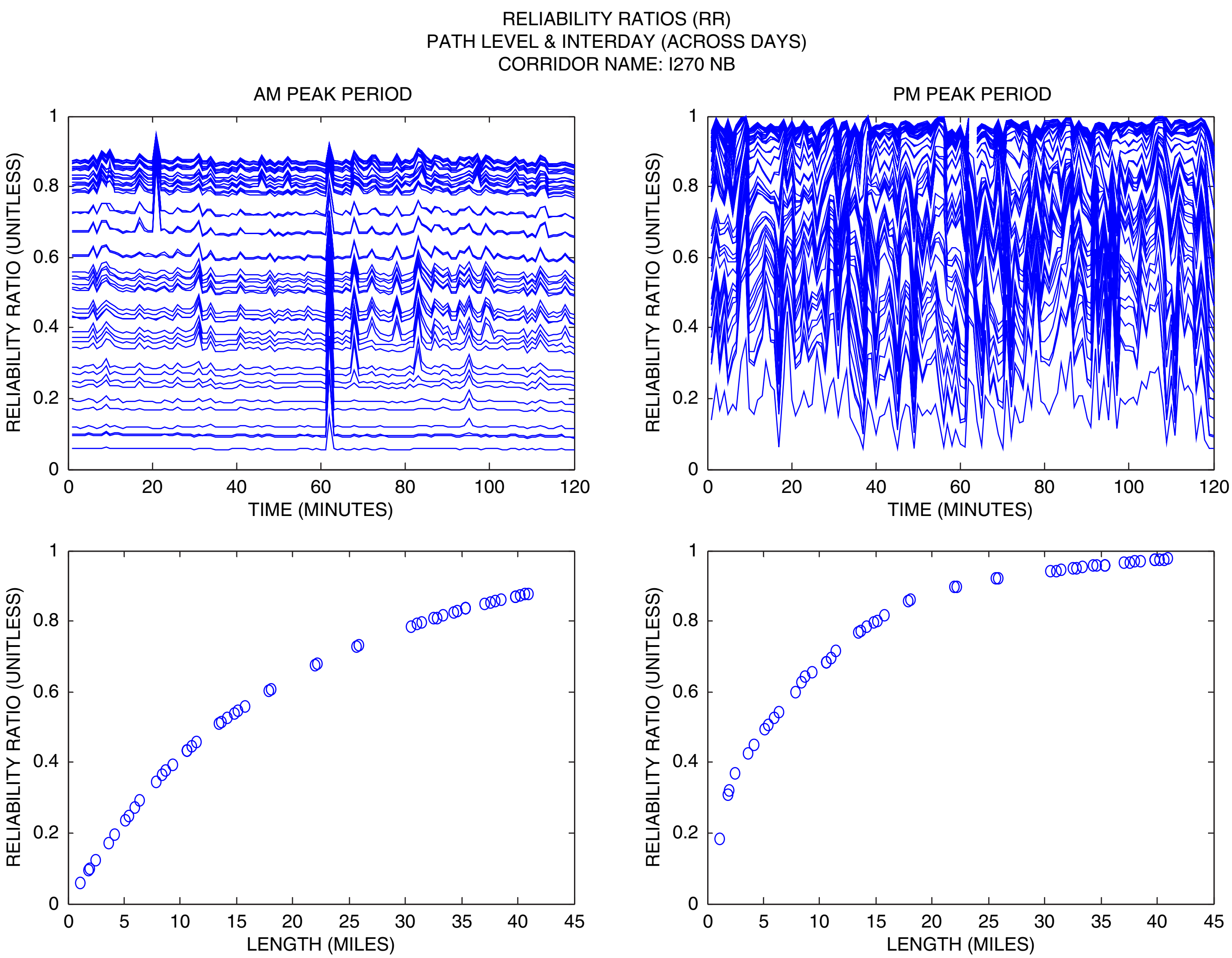


***Figure E.9. Analysis results on northbound I-270 corridor: left, AM peak period; right, PM peak period; top, reliability ratio over time; and bottom, average reliability ratio versus length.***

***Table E.5. TMC Segment Definitions on Southbound I-270 Corridor***

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110N04119 | I-270 | I-70/US-40 | FREDERICK | SOUTHBOUND | 0.828202 |
| 110-04118 | I-270 | MD-85/Exit 31 | FREDERICK | SOUTHBOUND | 0.85225 |
| 110N04118 | I-270 | MD-85/Exit 31 | FREDERICK | SOUTHBOUND | 0.512904 |
| 110-04117 | I-270 | MD-80/Exit 26 | FREDERICK | SOUTHBOUND | 4.835362 |
| 110N04117 | I-270 | MD-80/Exit 26 | FREDERICK | SOUTHBOUND | 0.162993 |
| 110-04116 | I-270 | MD-109/Exit 22 | MONTGOMERY | SOUTHBOUND | 3.554346 |
| 110N04116 | I-270 | MD-109/Exit 22 | MONTGOMERY | SOUTHBOUND | 0.173619 |
| 110-04115 | I-270 | MD-121 | MONTGOMERY | SOUTHBOUND | 3.446906 |
| 110N04115 | I-270 | MD-121 | MONTGOMERY | SOUTHBOUND | 0.219727 |
| 110-04114 | I-270 | Father Hurley Blvd/Exit 16 | MONTGOMERY | SOUTHBOUND | 2.257981 |
| 110N04114 | I-270 | Father Hurley Blvd/Exit 16 | MONTGOMERY | SOUTHBOUND | 0.720016 |
| 110-04113 | I-270 | MD-118/Exit 15 | MONTGOMERY | SOUTHBOUND | 0.350407 |
| 110N04113 | I-270 | MD-118/Exit 15 | MONTGOMERY | SOUTHBOUND | 0.622332 |
| 110-04112 | I-270 | Middlebrook Rd/Exit 13 | MONTGOMERY | SOUTHBOUND | 0.487799 |
| 110N04112 | I-270 | Middlebrook Rd/Exit 13 | MONTGOMERY | SOUTHBOUND | 0.276896 |
| 110-04111 | I-270 | MD-124/Quince Orchard Rd/Exit 11 | MONTGOMERY | SOUTHBOUND | 1.934977 |
| 110N04111 | I-270 | MD-124/Quince Orchard Rd/Exit 11 | MONTGOMERY | SOUTHBOUND | 0.256141 |
| 110-04110 | I-270 | MD-117/Exit 10 | MONTGOMERY | SOUTHBOUND | 0.624072 |
| 110N04110 | I-270 | MD-117/Exit 10 | MONTGOMERY | SOUTHBOUND | 0.277579 |
| 110-04109 | I-270 | I-370/Sam Eig Hwy/Exit 9 | MONTGOMERY | SOUTHBOUND | 0.70591 |
| 110N04109 | I-270 | I-370/Sam Eig Hwy/Exit 9 | MONTGOMERY | SOUTHBOUND | 0.920231 |
| 110-04108 | I-270 | Shady Grove Rd/Exit 8 | MONTGOMERY | SOUTHBOUND | 0.404345 |
| 110N04108 | I-270 | Shady Grove Rd/Exit 8 | MONTGOMERY | SOUTHBOUND | 0.419134 |
| 110-04107 | I-270 | MD-28/Montgomery Ave/Exit 6 | MONTGOMERY | SOUTHBOUND | 1.353658 |
| 110N04107 | I-270 | MD-28/Montgomery Ave/Exit 6 | MONTGOMERY | SOUTHBOUND | 0.456915 |
| 110-04106 | I-270 | MD-189/Falls Rd/Exit 5 | MONTGOMERY | SOUTHBOUND | 0.62836 |
| 110N04106 | I-270 | MD-189/Falls Rd/Exit 5 | MONTGOMERY | SOUTHBOUND | 0.574422 |
| 110-04105 | I-270 | Montrose Rd/Exit 4 | MONTGOMERY | SOUTHBOUND | 0.662475 |
| 110N04105 | I-270 | Montrose Rd/Exit 4 | MONTGOMERY | SOUTHBOUND | 0.538567 |
| 110-04104 | I-270 | I-270 | MONTGOMERY | SOUTHBOUND | 1.321096 |
| 110N04104 | I-270 | I-270 | MONTGOMERY | SOUTHBOUND | 0.191081 |
| 110-04103 | I-270 | MD-187/Old Georgetown Rd/Exit 1 | MONTGOMERY | SOUTHBOUND | 0.241165 |
| 110N04103 | I-270 | MD-187/Old Georgetown Rd/Exit 1 | MONTGOMERY | SOUTHBOUND | 0.808069 |
| 110-04102 | I-270 | I-495/MD-355 | MONTGOMERY | SOUTHBOUND | 1.091365 |
| 110-10538 | I-270 | MD-124/Montgomery Village Ave | MONTGOMERY | SOUTHBOUND | 0.290132 |
| 110N10538 | I-270 | MD-124/Montgomery Village Ave | MONTGOMERY | SOUTHBOUND | 0.302498 |
| 110-10537 | I-270 | MD-117/W Diamond Ave | MONTGOMERY | SOUTHBOUND | 0.577716 |
| 110N10537 | I-270 | MD-117/W Diamond Ave | MONTGOMERY | SOUTHBOUND | 0.277579 |

*(continued on next page)*

*Table E.5. TMC Segment Definitions on Southbound I-270 Corridor (continued)*

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110-10536 | I-270 | I-370 | MONTGOMERY | SOUTHBOUND | 0.70591 |
| 110N10536 | I-270 | I-370 | MONTGOMERY | SOUTHBOUND | 0.920231 |
| 110-10535 | I-270 | Shady Grove Rd | MONTGOMERY | SOUTHBOUND | 0.404345 |
| 110N10535 | I-270 | Shady Grove Rd | MONTGOMERY | SOUTHBOUND | 0.419134 |
| 110-10534 | I-270 | MD-28/W Montgomery Ave | MONTGOMERY | SOUTHBOUND | 1.634779 |
| 110N10534 | I-270 | MD-28/W Montgomery Ave | MONTGOMERY | SOUTHBOUND | 0.002175 |
| 110-10533 | I-270 | MD-189/Great Falls Rd | MONTGOMERY | SOUTHBOUND | 0.801979 |
| 110N10533 | I-270 | MD-189/Great Falls Rd | MONTGOMERY | SOUTHBOUND | 0.574422 |
| 110-10532 | I-270 | Montrose Rd | MONTGOMERY | SOUTHBOUND | 0.662475 |
| 110N10532 | I-270 | Montrose Rd | MONTGOMERY | SOUTHBOUND | 0.538567 |
| 110-10531 | I-270 | I-270 | MONTGOMERY | SOUTHBOUND | 0.347984 |

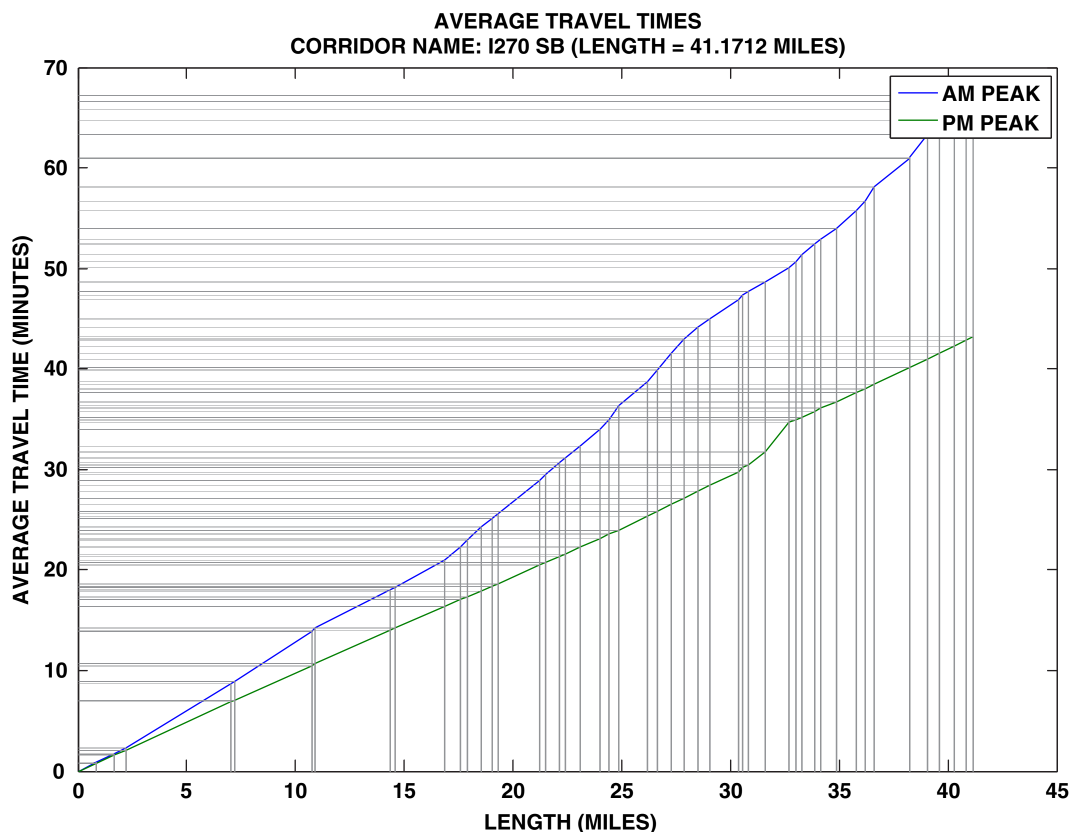


*Figure E.10. Average travel time versus length on southbound I-270 corridor.*

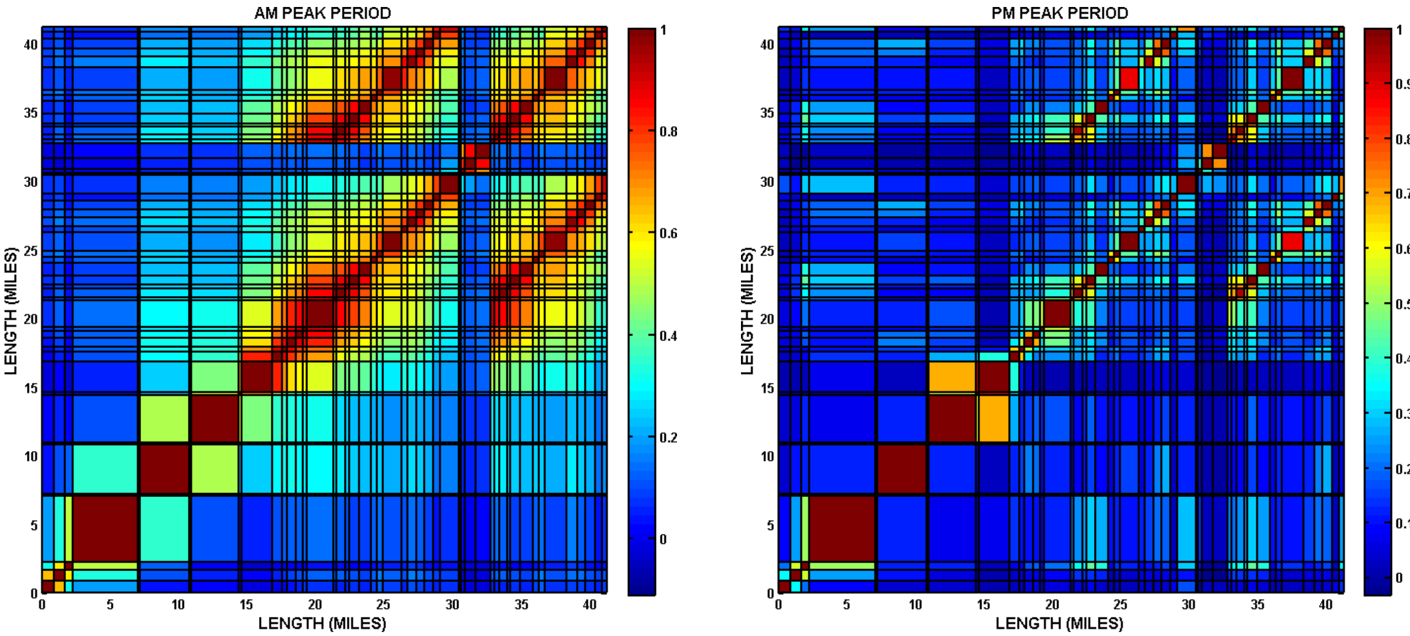


***Figure E.11. Travel time correlations on southbound I-270 corridor: left, AM peak period; right, PM peak period.***

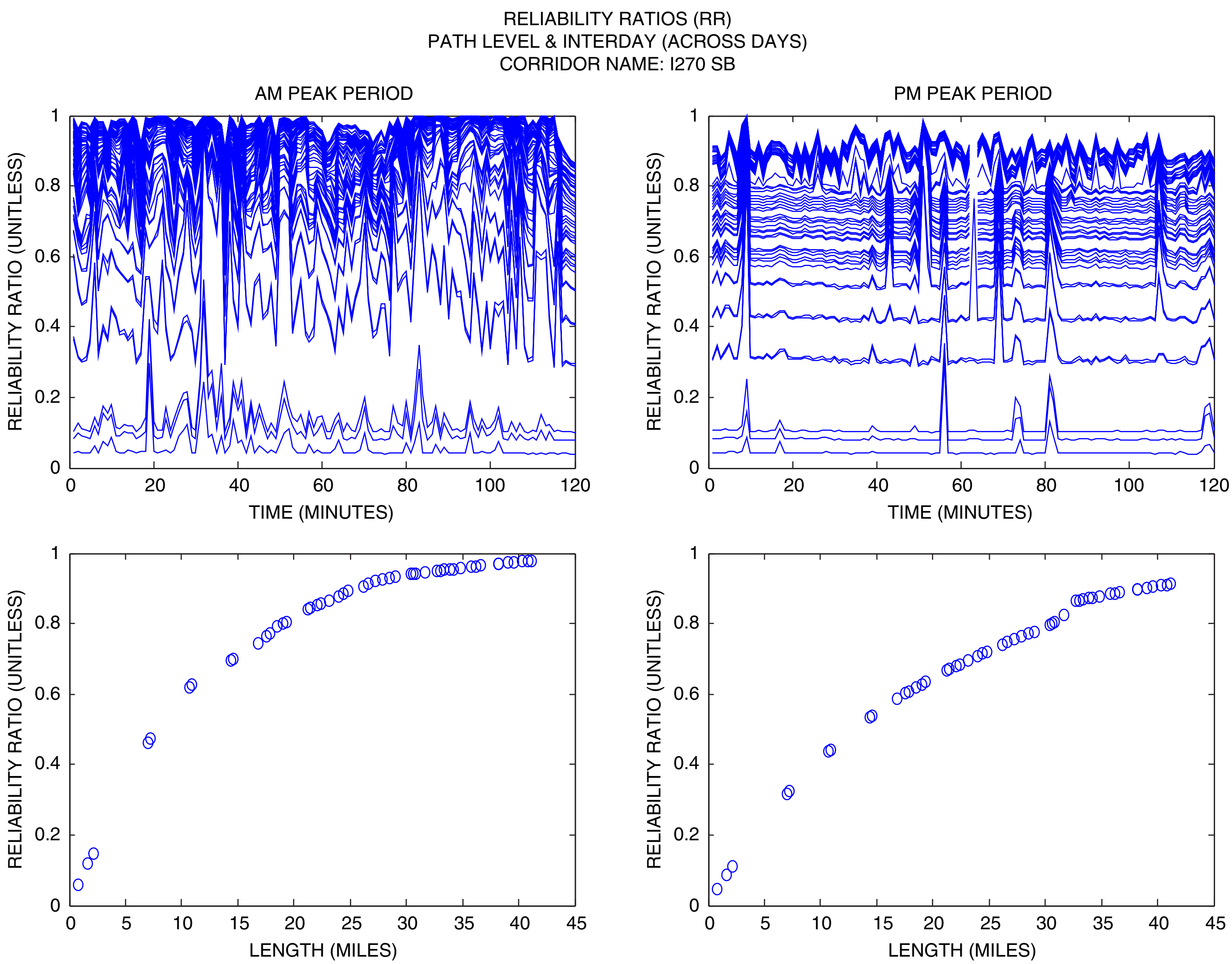


***Figure E.12. Analysis results on southbound I-270 corridor: left, AM peak period; right, PM peak period; top, reliability ratio over time; and bottom, average reliability ratio versus length.***

*Table E.6. TMC Segment Definitions on Clockwise (Inner Loop) I-495 Corridor*

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110+04615 | I-495 | Clara Barton Pkwy/Exit 41 | MONTGOMERY | CLOCKWISE | 0.213389 |
| 110P04615 | I-495 | Clara Barton Pkwy/Exit 41 | MONTGOMERY | CLOCKWISE | 0.35252 |
| 110+04616 | I-495 | Cabin John Pkwy/Exit 40 | MONTGOMERY | CLOCKWISE | 1.236897 |
| 110P04616 | I-495 | Cabin John Pkwy/Exit 40 | MONTGOMERY | CLOCKWISE | 0.444177 |
| 110+04617 | I-495 | MD-190/River Rd/Exit 39 | MONTGOMERY | CLOCKWISE | 0.090103 |
| 110P04617 | I-495 | MD-190/River Rd/Exit 39 | MONTGOMERY | CLOCKWISE | 0.00814 |
| 110+04618 | I-495 | I-270 Spur | MONTGOMERY | CLOCKWISE | 1.131072 |
| 110+04619 | I-495 | MD-187/Old Georgetown Rd/Exit 36 | MONTGOMERY | CLOCKWISE | 1.895954 |
| 110P04619 | I-495 | MD-187/Old Georgetown Rd/Exit 36 | MONTGOMERY | CLOCKWISE | 0.440262 |
| 110+04620 | I-495 | I-270/Exit 35 | MONTGOMERY | CLOCKWISE | 0.700753 |
| 110+04621 | I-495 | MD-355/Wisconsin Ave/Exit 34 | MONTGOMERY | CLOCKWISE | 0.046481 |
| 110P04621 | I-495 | MD-355/Wisconsin Ave/Exit 34 | MONTGOMERY | CLOCKWISE | 0.362587 |
| 110+04622 | I-495 | MD-185/Connecticut Ave/Exit 33 | MONTGOMERY | CLOCKWISE | 1.117899 |
| 110P04622 | I-495 | MD-185/Connecticut Ave/Exit 33 | MONTGOMERY | CLOCKWISE | 0.588466 |
| 110+04623 | I-495 | MD-97/Georgia Ave/Exit 31 | MONTGOMERY | CLOCKWISE | 1.609737 |
| 110P04623 | I-495 | MD-97/Georgia Ave/Exit 31 | MONTGOMERY | CLOCKWISE | 0.390177 |
| 110+04624 | I-495 | US-29/Colesville Rd/Exit 30 | MONTGOMERY | CLOCKWISE | 1.067503 |
| 110P04624 | I-495 | US-29/Colesville Rd/Exit 30 | MONTGOMERY | CLOCKWISE | 0.422055 |
| 110+04625 | I-495 | MD-193/University Blvd/Exit 29 | MONTGOMERY | CLOCKWISE | 0.240668 |
| 110P04625 | I-495 | MD-193/University Blvd/Exit 29 | MONTGOMERY | CLOCKWISE | 0.435104 |
| 110+04626 | I-495 | MD-650/New Hampshire Ave/Exit 28 | MONTGOMERY | CLOCKWISE | 1.091241 |
| 110P04626 | I-495 | MD-650/New Hampshire Ave/Exit 28 | MONTGOMERY | CLOCKWISE | 0.627241 |
| 110+04627 | I-495 | Exit 27 | PRINCE GEORGE’S | CLOCKWISE | 0.499916 |

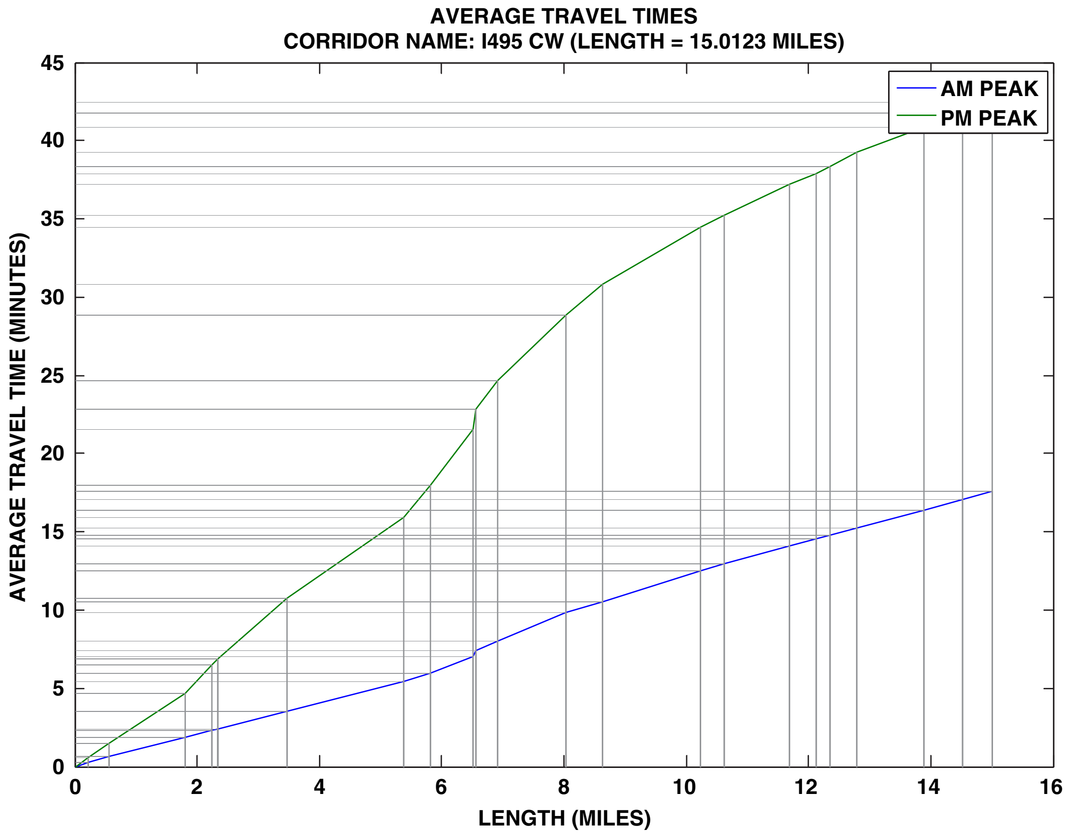


*Figure E.13. Average travel time versus length on clockwise (inner loop) I-495 corridor.*

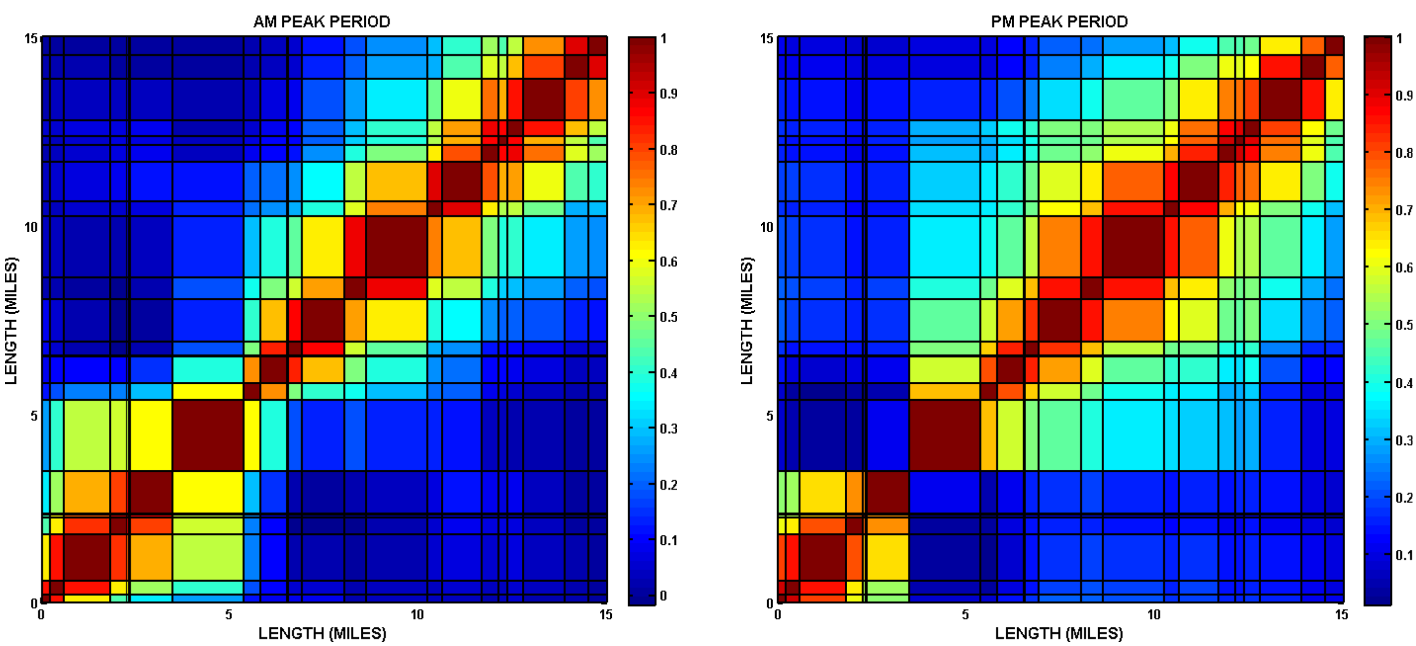


*Figure E.14. Travel time correlations on clockwise (inner loop) I-495 corridor: left, AM peak period; right, PM peak period.*

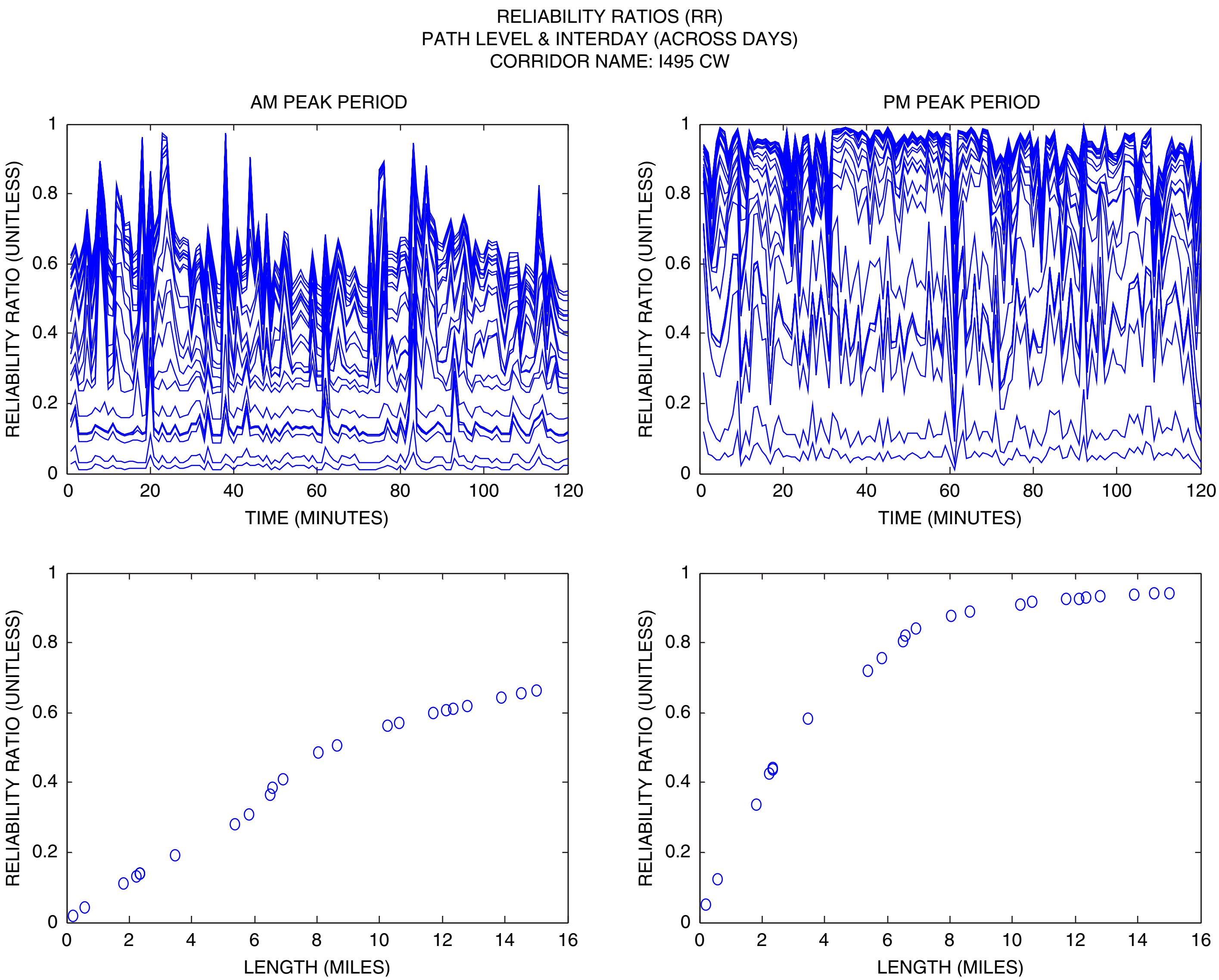


***Figure E.15. Analysis results on clockwise (inner loop) I-495 corridor: left, AM peak period; right, PM peak period; top, reliability ratio over time; and bottom, average reliability ratio versus length.***

*Table E.7. TMC Segment Definitions on Counterclockwise (Outer Loop) I-495 Corridor*

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110N04627 | I-495 | Exit 27 | PRINCE GEORGE'S | COUNTERCLOCKWISE | 0.942975 |
| 110-04626 | I-495 | MD-650/New Hampshire Ave/Exit 28 | MONTGOMERY | COUNTERCLOCKWISE | 0.675089 |
| 110N04626 | I-495 | MD-650/New Hampshire Ave/Exit 28 | MONTGOMERY | COUNTERCLOCKWISE | 0.556153 |
| 110-04625 | I-495 | MD-193/University Blvd/Exit 29 | MONTGOMERY | COUNTERCLOCKWISE | 1.139523 |
| 110N04625 | I-495 | MD-193/University Blvd/Exit 29 | MONTGOMERY | COUNTERCLOCKWISE | 0.22389 |
| 110-04624 | I-495 | US-29/Colesville Rd/Exit 30 | MONTGOMERY | COUNTERCLOCKWISE | 0.598843 |
| 110N04624 | I-495 | US-29/Colesville Rd/Exit 30 | MONTGOMERY | COUNTERCLOCKWISE | 0.258067 |
| 110-04623 | I-495 | MD-97/Georgia Ave/Exit 31 | MONTGOMERY | COUNTERCLOCKWISE | 1.023011 |
| 110N04623 | I-495 | MD-97/Georgia Ave/Exit 31 | MONTGOMERY | COUNTERCLOCKWISE | 0.365756 |
| 110-04622 | I-495 | MD-185/Connecticut Ave/Exit 33 | MONTGOMERY | COUNTERCLOCKWISE | 1.60781 |
| 110N04622 | I-495 | MD-185/Connecticut Ave/Exit 33 | MONTGOMERY | COUNTERCLOCKWISE | 0.701871 |
| 110-04621 | I-495 | MD-355/Wisconsin Ave/Exit 34 | MONTGOMERY | COUNTERCLOCKWISE | 1.118706 |
| 110N04621 | I-495 | MD-355/Wisconsin Ave/Exit 34 | MONTGOMERY | COUNTERCLOCKWISE | 0.424975 |
| 110-04620 | I-495 | I-270/Exit 35 | MONTGOMERY | COUNTERCLOCKWISE | 0.01423 |
| 110-04619 | I-495 | MD-187/Old Georgetown Rd/Exit 36 | MONTGOMERY | COUNTERCLOCKWISE | 0.785325 |
| 110N04619 | I-495 | MD-187/Old Georgetown Rd/Exit 36 | MONTGOMERY | COUNTERCLOCKWISE | 0.42802 |
| 110-04618 | I-495 | I-270 Spur | MONTGOMERY | COUNTERCLOCKWISE | 1.780062 |
| 110-04617 | I-495 | MD-190/River Rd/Exit 39 | MONTGOMERY | COUNTERCLOCKWISE | 1.251686 |
| 110N04617 | I-495 | MD-190/River Rd/Exit 39 | MONTGOMERY | COUNTERCLOCKWISE | 0.008575 |
| 110-04616 | I-495 | Cabin John Pkwy/Exit 40 | MONTGOMERY | COUNTERCLOCKWISE | 0.032499 |
| 110N04616 | I-495 | Cabin John Pkwy/Exit 40 | MONTGOMERY | COUNTERCLOCKWISE | 0.554413 |
| 110-04615 | I-495 | Clara Barton Pkwy/Exit 41 | MONTGOMERY | COUNTERCLOCKWISE | 1.143376 |
| 110N04615 | I-495 | Clara Barton Pkwy/Exit 41 | MONTGOMERY | COUNTERCLOCKWISE | 0.389618 |

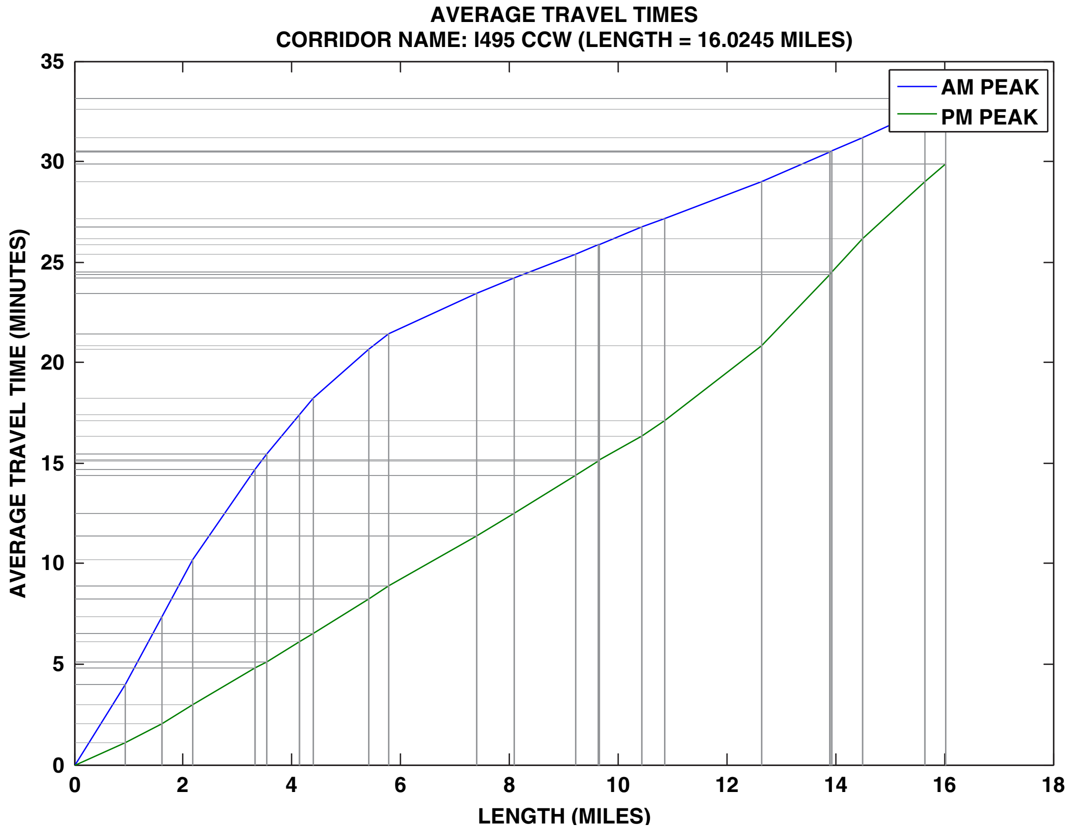


*Figure E.16. Average travel time versus length on counterclockwise (outer loop) I-495 corridor.*

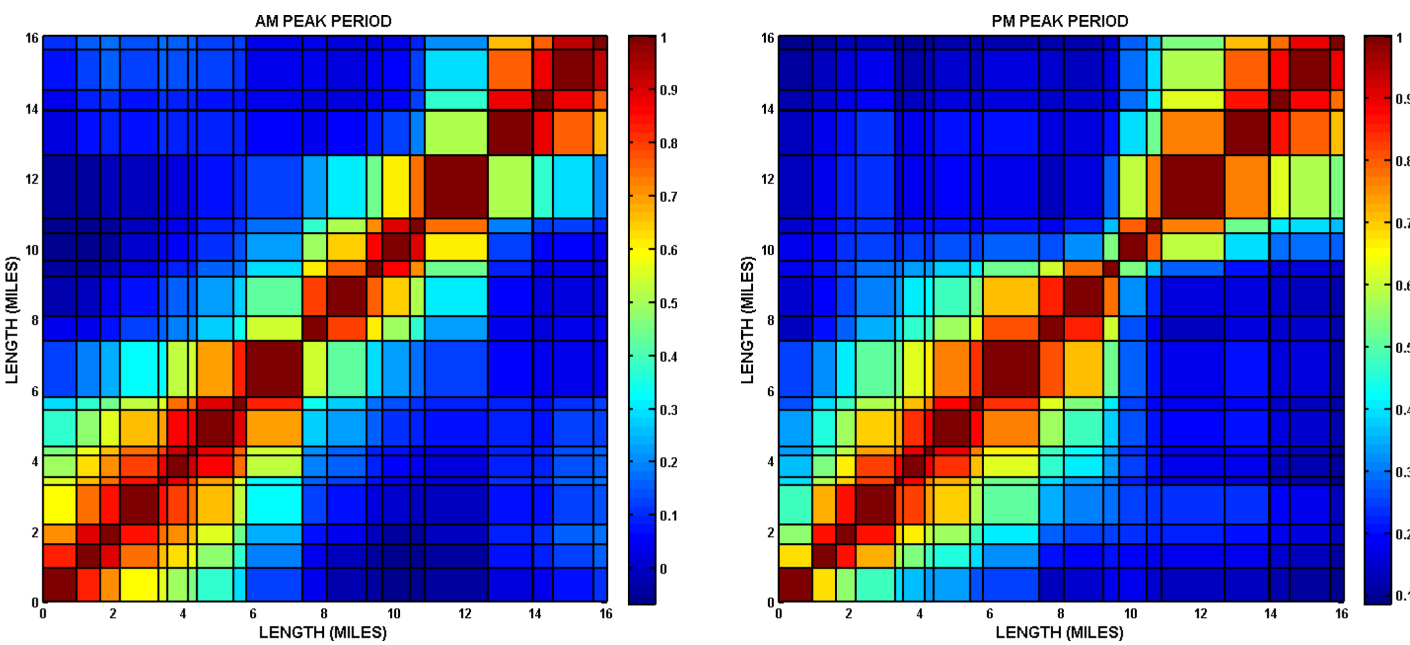


*Figure E.17. Travel time correlations on counterclockwise (outer loop) I-495 corridor: left, AM peak period; right, PM peak period.*

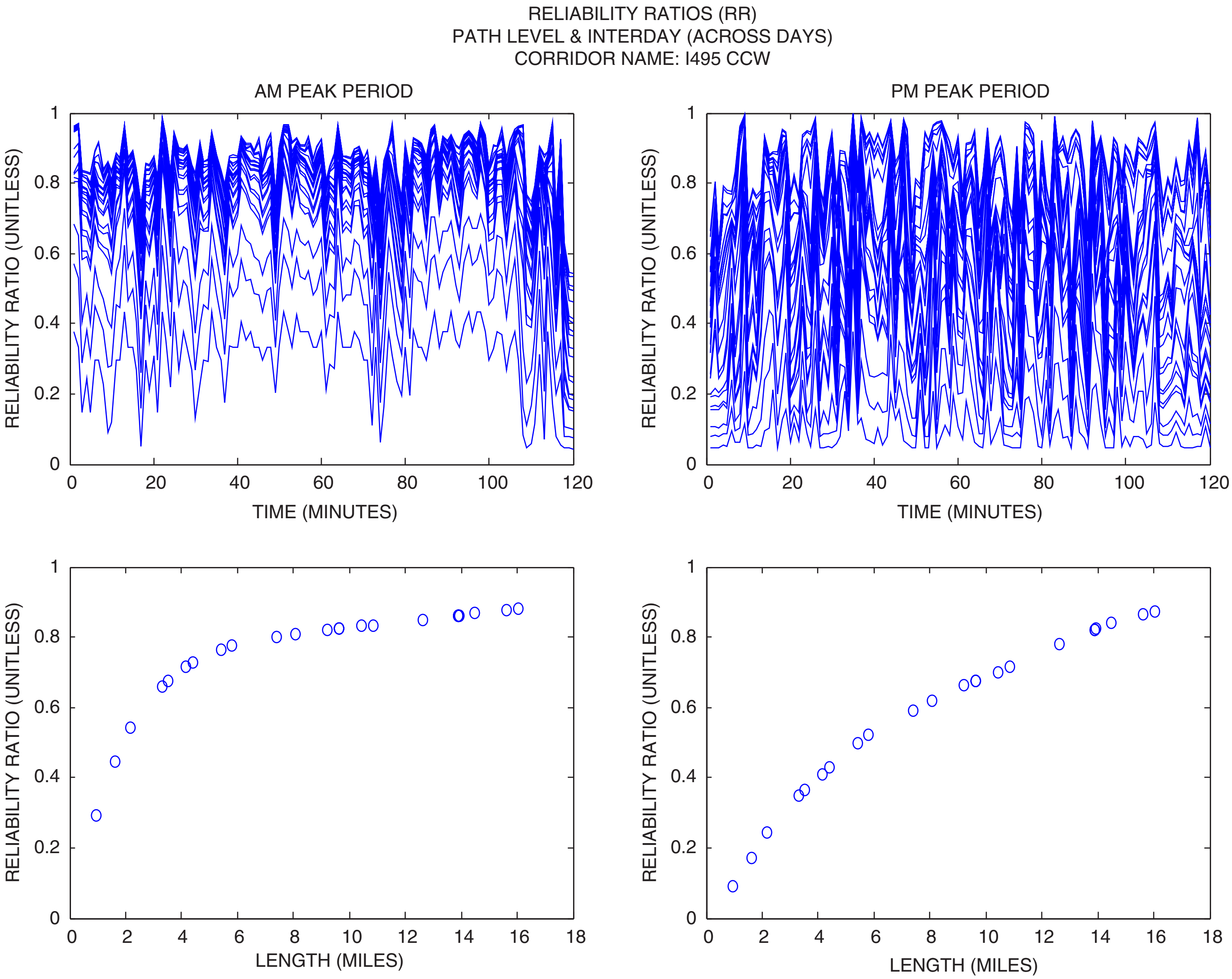


***Figure E.18. Analysis results on counterclockwise (outer loop) I-495 corridor: left, AM peak period; right, PM peak period; top, reliability ratio over time; and bottom, average reliability ratio versus length.***

*Table E.8. TMC Segment Definitions on Northbound MD-295 Corridor*

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110+04265 | MD-295 | US-50/MD-201/Kenilworth Ave | PRINCE GEORGE'S | NORTHBOUND | 0.319213 |
| 110+04266 | MD-295 | MD-202 | PRINCE GEORGE'S | NORTHBOUND | 0.902521 |
| 110P04266 | MD-295 | MD-202 | PRINCE GEORGE'S | NORTHBOUND | 0.186731 |
| 110+04267 | MD-295 | MD-450 | PRINCE GEORGE'S | NORTHBOUND | 0.09756 |
| 110P04267 | MD-295 | MD-450 | PRINCE GEORGE'S | NORTHBOUND | 0.456294 |
| 110+04268 | MD-295 | Riverdale Rd | PRINCE GEORGE'S | NORTHBOUND | 1.176062 |
| 110P04268 | MD-295 | Riverdale Rd | PRINCE GEORGE'S | NORTHBOUND | 0.48842 |
| 110+04269 | MD-295 | I-495/I-95 | PRINCE GEORGE'S | NORTHBOUND | 1.818714 |
| 110P04269 | MD-295 | I-495/I-95 | PRINCE GEORGE'S | NORTHBOUND | 0.555034 |
| 110+04270 | MD-295 | MD-193 | PRINCE GEORGE'S | NORTHBOUND | 0.242284 |
| 110P04270 | MD-295 | MD-193 | PRINCE GEORGE'S | NORTHBOUND | 0.18555 |
| 110+04271 | MD-295 | Goddard Rd | PRINCE GEORGE'S | NORTHBOUND | 0.828948 |
| 110P04271 | MD-295 | Goddard Rd | PRINCE GEORGE'S | NORTHBOUND | 0.29212 |
| 110+04272 | MD-295 | Powder Mill Rd | PRINCE GEORGE'S | NORTHBOUND | 1.605635 |
| 110P04272 | MD-295 | Powder Mill Rd | PRINCE GEORGE'S | NORTHBOUND | 0.471518 |
| 110+04273 | MD-295 | MD-197/Exit 11 | PRINCE GEORGE'S | NORTHBOUND | 1.121006 |
| 110P04273 | MD-295 | MD-197/Exit 11 | PRINCE GEORGE'S | NORTHBOUND | 0.711814 |
| 110+04274 | MD-295 | Arundel/Prince George's Co Line (Laurel) (South) | PRINCE GEORGE'S | NORTHBOUND | 0.631032 |
| 110+04494 | MD-295 | Arundel/Prince George's Co Line (Laurel) (North) | ANNE ARUNDEL | NORTHBOUND | 0.016902 |
| 110+04495 | MD-295 | MD-198 | ANNE ARUNDEL | NORTHBOUND | 2.148428 |
| 110P04495 | MD-295 | MD-198 | ANNE ARUNDEL | NORTHBOUND | 0.680682 |
| 110+04496 | MD-295 | MD-32 | ANNE ARUNDEL | NORTHBOUND | 0.944217 |
| 110P04496 | MD-295 | MD-32 | ANNE ARUNDEL | NORTHBOUND | 0.724304 |
| 110+04497 | MD-295 | Canine Rd | ANNE ARUNDEL | NORTHBOUND | 0.167902 |
| 110P04497 | MD-295 | Canine Rd | ANNE ARUNDEL | NORTHBOUND | 0.2654 |
| 110+04498 | MD-295 | MD-175 | ANNE ARUNDEL | NORTHBOUND | 1.275796 |
| 110P04498 | MD-295 | MD-175 | ANNE ARUNDEL | NORTHBOUND | 0.592008 |
| 110+04499 | MD-295 | MD-100 | ANNE ARUNDEL | NORTHBOUND | 1.678588 |
| 110P04499 | MD-295 | MD-100 | ANNE ARUNDEL | NORTHBOUND | 0.790234 |
| 110+04500 | MD-295 | I-195 | ANNE ARUNDEL | NORTHBOUND | 2.180058 |
| 110P04500 | MD-295 | I-195 | ANNE ARUNDEL | NORTHBOUND | 0.805024 |
| 110+04501 | MD-295 | Nursery Rd | ANNE ARUNDEL | NORTHBOUND | 0.528811 |
| 110P04501 | MD-295 | Nursery Rd | ANNE ARUNDEL | NORTHBOUND | 0.529806 |
| 110+04502 | MD-295 | I-695 | ANNE ARUNDEL | NORTHBOUND | 0.714921 |
| 110P04502 | MD-295 | I-695 | ANNE ARUNDEL | NORTHBOUND | 0.438708 |
| 110+04503 | MD-295 | I-895/Harbor Tunnel Trwy | BALTIMORE | NORTHBOUND | 0.734743 |
| 110P04503 | MD-295 | I-895/Harbor Tunnel Trwy | BALTIMORE | NORTHBOUND | 0.110671 |
| 110+04504 | MD-295 | MD-648/Waterview Ave/Annapolis Rd | BALTIMORE | NORTHBOUND | 2.065471 |

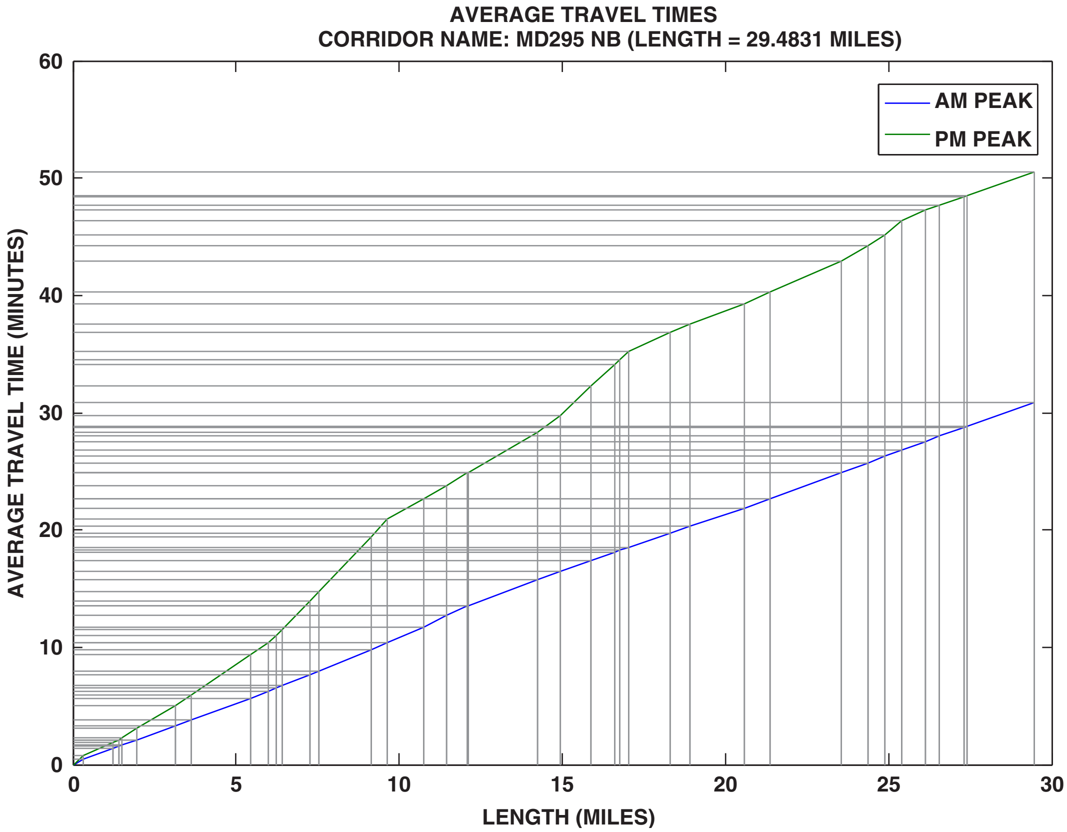


*Figure E.19. Average travel time versus length on northbound MD-295 corridor.*

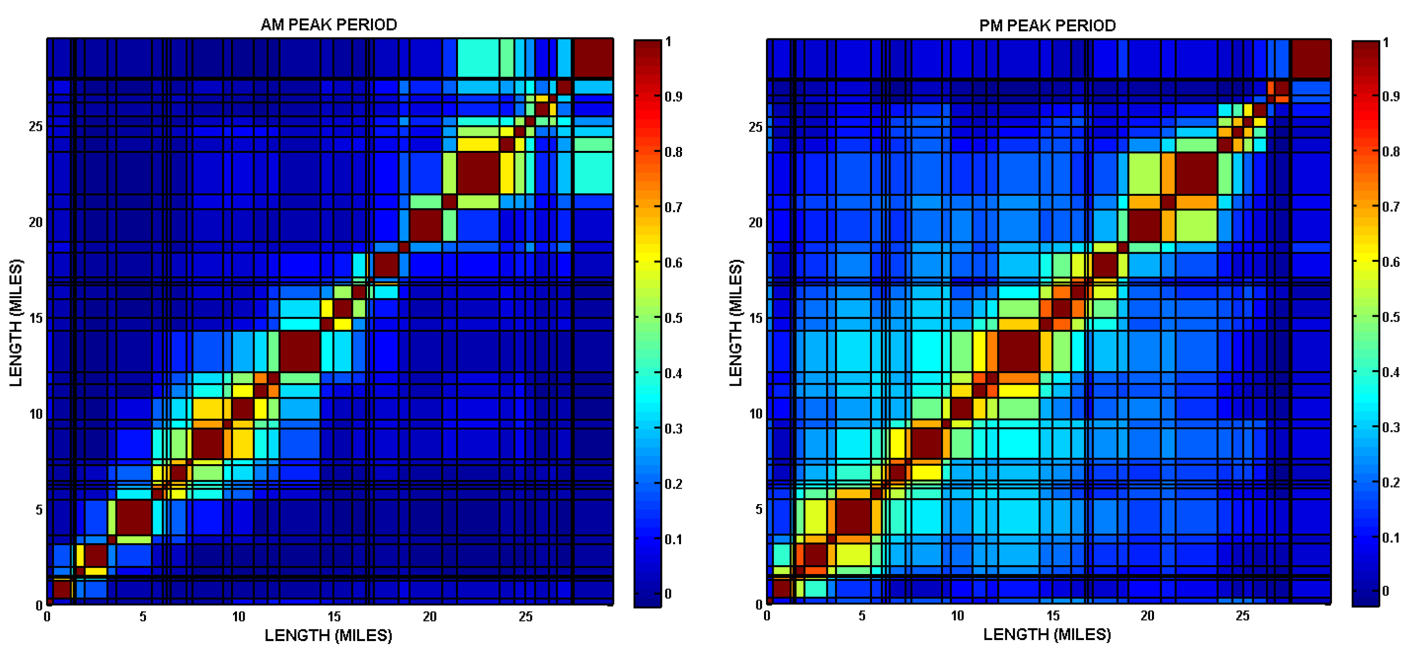


*Figure E.20. Travel time correlations on northbound MD-295 corridor: left, AM peak period; right, PM peak period.*

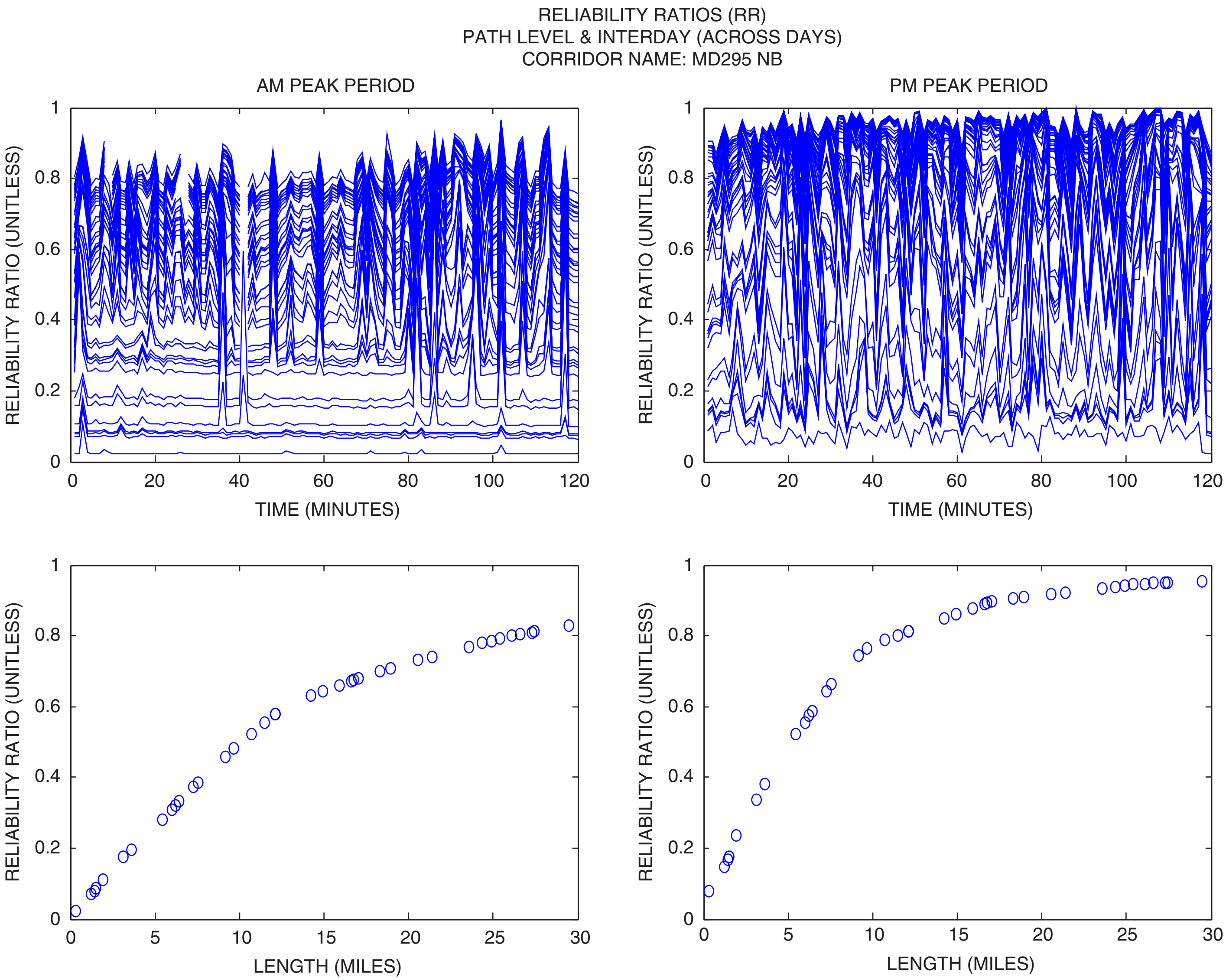


***Figure E.21. Analysis results on northbound MD-295 corridor: left, AM peak period; right, PM peak period; top, reliability ratio over time; and bottom, average reliability ratio versus length.***

### Table E.9. TMC Segment Definitions on Southbound MD-295 Corridor

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110-04503 | MD-295 | I-895/Harbor Tunnel Trwy | BALTIMORE | SOUTHBOUND | 1.873956 |
| 110N04503 | MD-295 | I-895/Harbor Tunnel Trwy | BALTIMORE | SOUTHBOUND | 0.051638 |
| 110-04502 | MD-295 | I-695 | ANNE ARUNDEL | SOUTHBOUND | 0.813164 |
| 110N04502 | MD-295 | I-695 | ANNE ARUNDEL | SOUTHBOUND | 0.408819 |
| 110-04501 | MD-295 | Nursery Rd | ANNE ARUNDEL | SOUTHBOUND | 0.669745 |
| 110N04501 | MD-295 | Nursery Rd | ANNE ARUNDEL | SOUTHBOUND | 0.555532 |
| 110-04500 | MD-295 | I-195 | ANNE ARUNDEL | SOUTHBOUND | 0.568705 |
| 110N04500 | MD-295 | I-195 | ANNE ARUNDEL | SOUTHBOUND | 0.752888 |
| 110-04499 | MD-295 | MD-100 | ANNE ARUNDEL | SOUTHBOUND | 2.189689 |
| 110N04499 | MD-295 | MD-100 | ANNE ARUNDEL | SOUTHBOUND | 0.830688 |
| 110-04498 | MD-295 | MD-175 | ANNE ARUNDEL | SOUTHBOUND | 1.666906 |
| 110N04498 | MD-295 | MD-175 | ANNE ARUNDEL | SOUTHBOUND | 0.609345 |
| 110-04497 | MD-295 | Canine Rd | ANNE ARUNDEL | SOUTHBOUND | 1.222791 |
| 110N04497 | MD-295 | Canine Rd | ANNE ARUNDEL | SOUTHBOUND | 0.30113 |
| 110-04496 | MD-295 | MD-32 | ANNE ARUNDEL | SOUTHBOUND | 0.058474 |
| 110N04496 | MD-295 | MD-32 | ANNE ARUNDEL | SOUTHBOUND | 0.791104 |
| 110-04495 | MD-295 | MD-198 | ANNE ARUNDEL | SOUTHBOUND | 1.138902 |
| 110N04495 | MD-295 | MD-198 | ANNE ARUNDEL | SOUTHBOUND | 0.463937 |
| 110-04494 | MD-295 | Arundel/Prince George's Co Line (Laurel) (North) | ANNE ARUNDEL | SOUTHBOUND | 2.234741 |
| 110-04274 | MD-295 | Arundel/Prince George's Co Line (Laurel) (South) | PRINCE GEORGE'S | SOUTHBOUND | 0.014976 |
| 110-04273 | MD-295 | MD-197/Exit 11 | PRINCE GEORGE'S | SOUTHBOUND | 0.437714 |
| 110N04273 | MD-295 | MD-197/Exit 11 | PRINCE GEORGE'S | SOUTHBOUND | 0.799183 |
| 110-04272 | MD-295 | Powder Mill Rd | PRINCE GEORGE'S | SOUTHBOUND | 1.232733 |
| 110N04272 | MD-295 | Powder Mill Rd | PRINCE GEORGE'S | SOUTHBOUND | 0.497182 |
| 110-04271 | MD-295 | Goddard Rd | PRINCE GEORGE'S | SOUTHBOUND | 1.698659 |
| 110N04271 | MD-295 | Goddard Rd | PRINCE GEORGE'S | SOUTHBOUND | 0.172936 |
| 110-04270 | MD-295 | MD-193 | PRINCE GEORGE'S | SOUTHBOUND | 0.836653 |
| 110N04270 | MD-295 | MD-193 | PRINCE GEORGE'S | SOUTHBOUND | 0.312626 |
| 110-04269 | MD-295 | I-495/I-95 | PRINCE GEORGE'S | SOUTHBOUND | 0.059095 |
| 110N04269 | MD-295 | I-495/I-95 | PRINCE GEORGE'S | SOUTHBOUND | 0.538132 |
| 110-04268 | MD-295 | Riverdale Rd | PRINCE GEORGE'S | SOUTHBOUND | 1.896761 |
| 110N04268 | MD-295 | Riverdale Rd | PRINCE GEORGE'S | SOUTHBOUND | 0.467293 |
| 110-04267 | MD-295 | MD-450 | PRINCE GEORGE'S | SOUTHBOUND | 1.183581 |
| 110N04267 | MD-295 | MD-450 | PRINCE GEORGE'S | SOUTHBOUND | 0.254463 |
| 110-04266 | MD-295 | MD-202 | PRINCE GEORGE'S | SOUTHBOUND | 0.088984 |
| 110N04266 | MD-295 | MD-202 | PRINCE GEORGE'S | SOUTHBOUND | 0.232217 |
| 110-04265 | MD-295 | US-50/MD-201/Kenilworth Ave | PRINCE GEORGE'S | SOUTHBOUND | 1.046313 |
| 110-04264 | MD-295 | Eastern Ave | PRINCE GEORGE'S | SOUTHBOUND | 0.329591 |

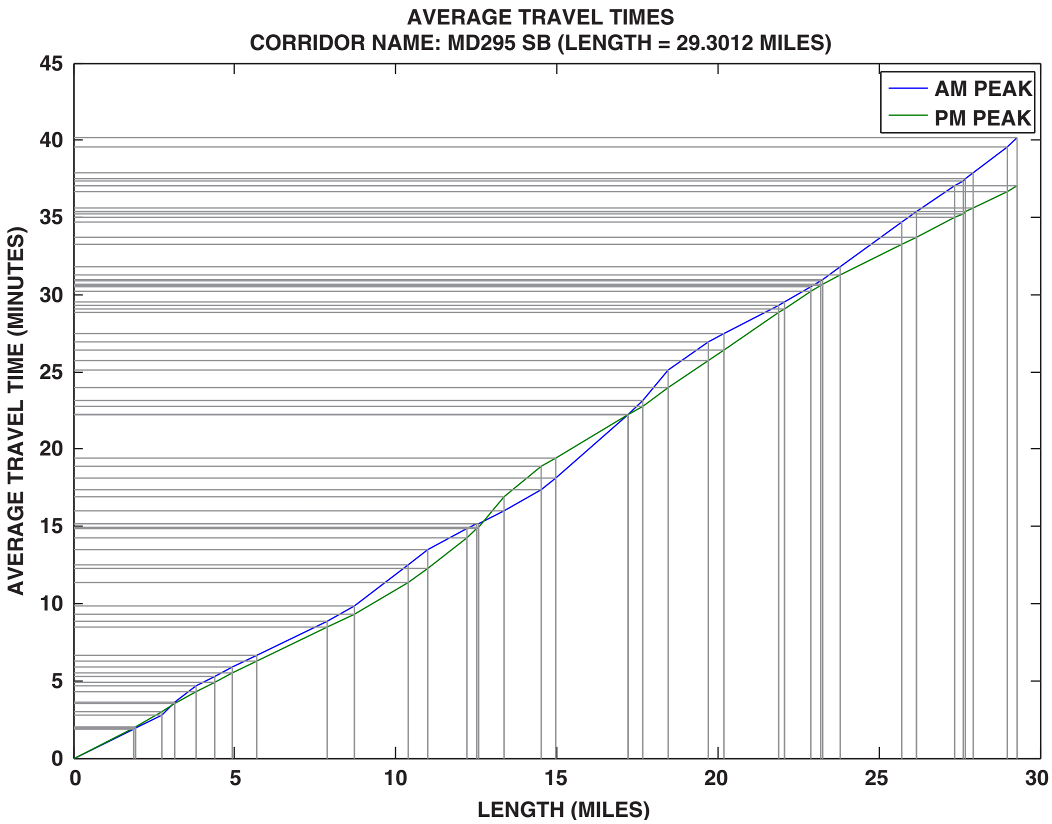


*Figure E.22. Average travel time versus length on southbound MD-295 corridor.*

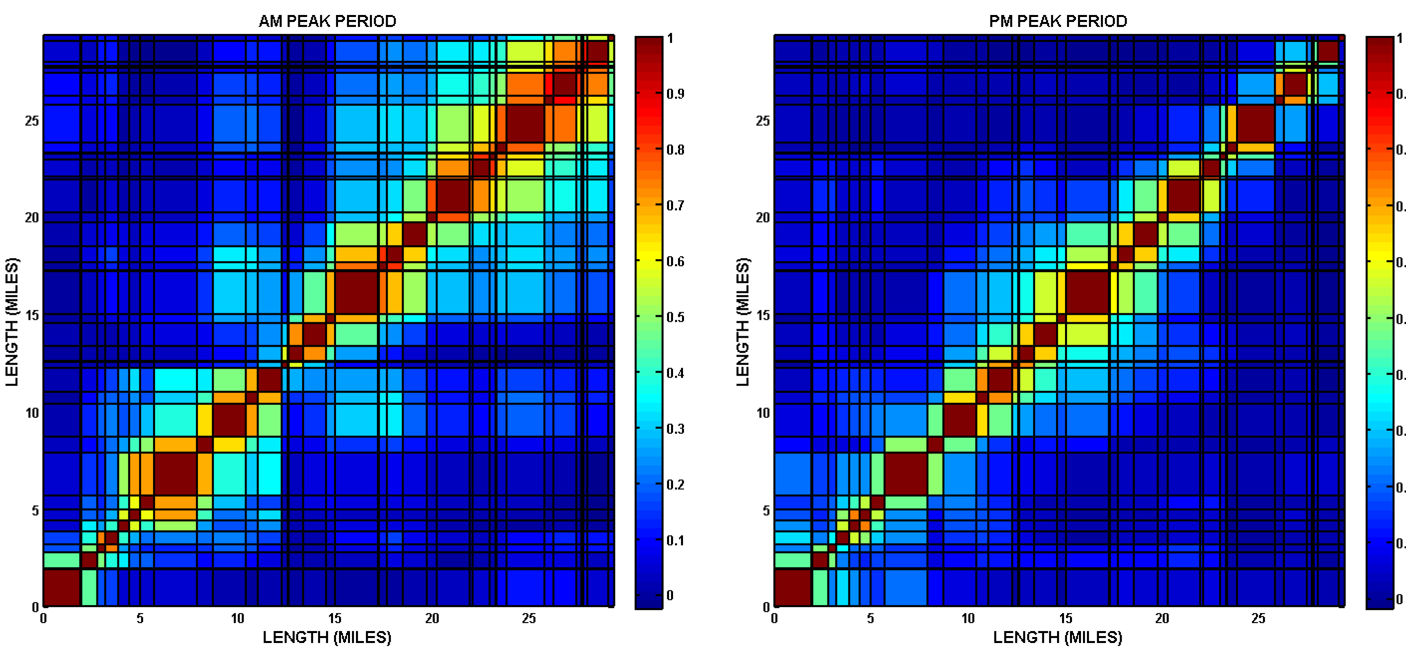


*Figure E.23. Travel time correlations on southbound MD-295 corridor: left, AM peak period; right, PM peak period.*

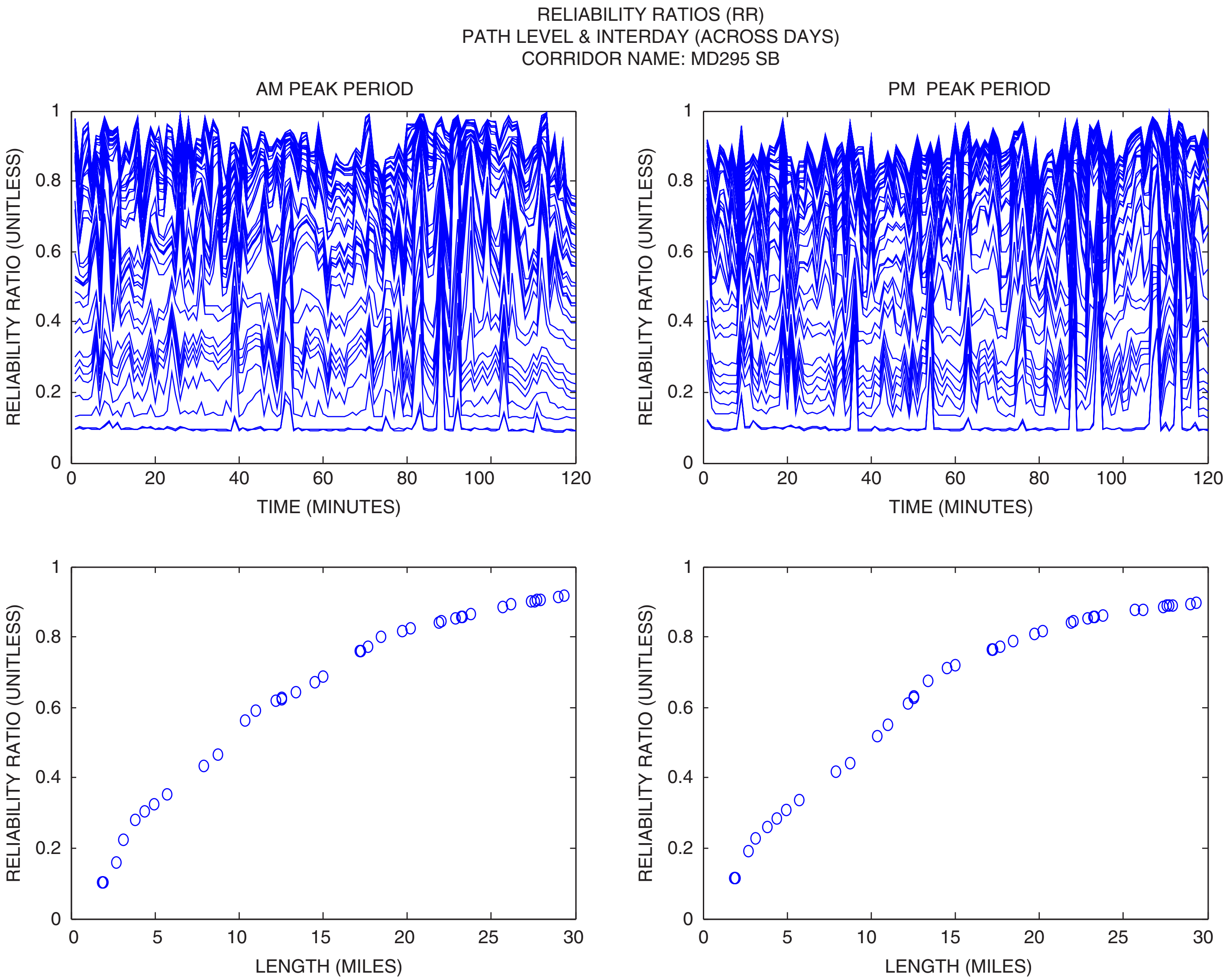


*Figure E.24. Analysis results on southbound MD-295 corridor: left, AM peak period; right, PM peak period; top, reliability ratio over time; and bottom, average reliability ratio versus length.*

*Table E.10. TMC Segment Definitions on Northbound US-29 Corridor*

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110+05898 | US-29 | Cherry Hill Rd/Randolph Rd | MONTGOMERY | NORTHBOUND | 1.58022 |
| 110P05898 | US-29 | Cherry Hill Rd/Randolph Rd | MONTGOMERY | NORTHBOUND | 0.508678 |
| 110+05899 | US-29 | Fairland Rd | MONTGOMERY | NORTHBOUND | 0.539624 |
| 110P05899 | US-29 | Fairland Rd | MONTGOMERY | NORTHBOUND | 0.059841 |
| 110+05900 | US-29 | Briggs Chaney Rd | MONTGOMERY | NORTHBOUND | 0.453622 |
| 110P05900 | US-29 | Briggs Chaney Rd | MONTGOMERY | NORTHBOUND | 0.598781 |
| 110+05901 | US-29 | Greencastle Rd | MONTGOMERY | NORTHBOUND | 0.754193 |
| 110+05902 | US-29 | MD-198/Sandy Spring Rd | MONTGOMERY | NORTHBOUND | 0.93123 |
| 110P05902 | US-29 | MD-198/Sandy Spring Rd | MONTGOMERY | NORTHBOUND | 0.648679 |
| 110+06887 | US-29 | Dustin Rd | MONTGOMERY | NORTHBOUND | 0.373896 |
| 110P06887 | US-29 | Dustin Rd | MONTGOMERY | NORTHBOUND | 0.306909 |
| 110+05241 | US-29 | Howard/Montgomery County Line | HOWARD | NORTHBOUND | 0.474066 |
| 110+05242 | US-29 | Old Columbia Rd | HOWARD | NORTHBOUND | 0.569762 |
| 110P05242 | US-29 | Old Columbia Rd | HOWARD | NORTHBOUND | 0.050209 |
| 110+05243 | US-29 | MD-216 | HOWARD | NORTHBOUND | 0.778987 |
| 110P05243 | US-29 | MD-216 | HOWARD | NORTHBOUND | 0.392103 |
| 110+05244 | US-29 | Johns Hopkins Rd/Exit 15 | HOWARD | NORTHBOUND | 0.416027 |
| 110P05244 | US-29 | Johns Hopkins Rd/Exit 15 | HOWARD | NORTHBOUND | 0.616864 |
| 110+05245 | US-29 | MD-32/Exit 16 | HOWARD | NORTHBOUND | 1.020028 |
| 110P05245 | US-29 | MD-32/Exit 16 | HOWARD | NORTHBOUND | 0.840444 |
| 110+05246 | US-29 | Brokenland Pkwy/Exit 18 | HOWARD | NORTHBOUND | 0.839449 |
| 110P05246 | US-29 | Brokenland Pkwy/Exit 18 | HOWARD | NORTHBOUND | 0.673908 |
| 110+05247 | US-29 | MD-175 | HOWARD | NORTHBOUND | 1.152759 |
| 110P05247 | US-29 | MD-175 | HOWARD | NORTHBOUND | 0.609531 |
| 110+05248 | US-29 | MD-108 | HOWARD | NORTHBOUND | 0.480466 |
| 110P05248 | US-29 | MD-108 | HOWARD | NORTHBOUND | 0.654334 |
| 110+05249 | US-29 | MD-100/Exit 22 | HOWARD | NORTHBOUND | 0.450826 |
| 110P05249 | US-29 | MD-100/Exit 22 | HOWARD | NORTHBOUND | 0.615745 |
| 110+05250 | US-29 | MD-103 | HOWARD | NORTHBOUND | 0.045052 |
| 110P05250 | US-29 | MD-103 | HOWARD | NORTHBOUND | 0.44573 |
| 110+05251 | US-29 | US-40 | HOWARD | NORTHBOUND | 0.628484 |
| 110P05251 | US-29 | US-40 | HOWARD | NORTHBOUND | 0.822858 |
| 110+05252 | US-29 | I-70 | HOWARD | NORTHBOUND | 0.457599 |
| 110P05252 | US-29 | I-70 | HOWARD | NORTHBOUND | 0.859458 |

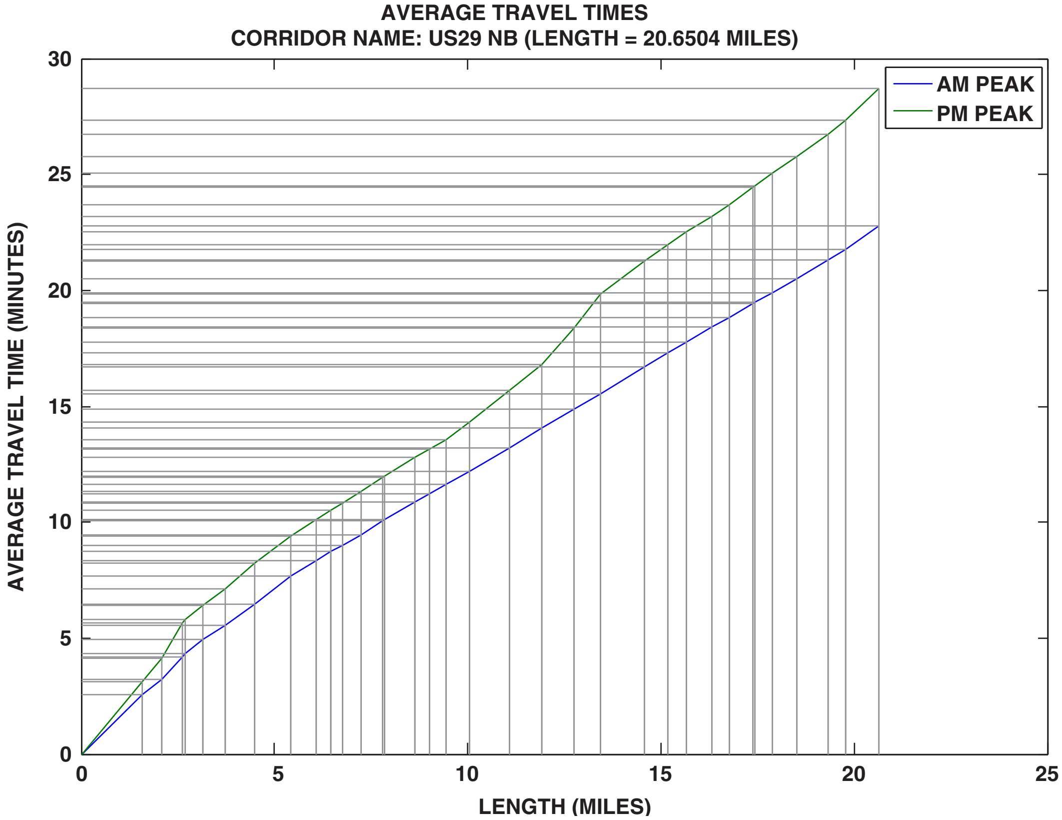


*Figure E.25. Average travel time versus length on northbound US-29 corridor.*

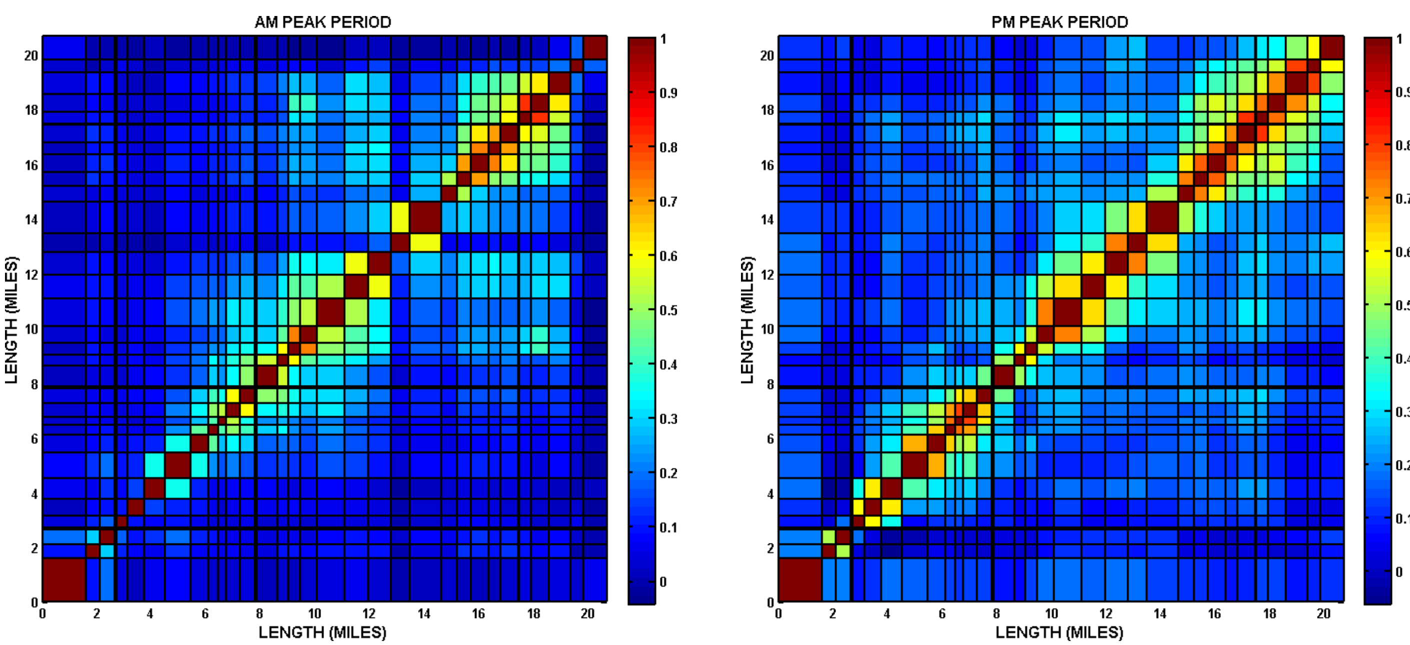


*Figure E.26. Travel time correlations on northbound US-29 corridor: left, AM peak period; right, PM peak period.*

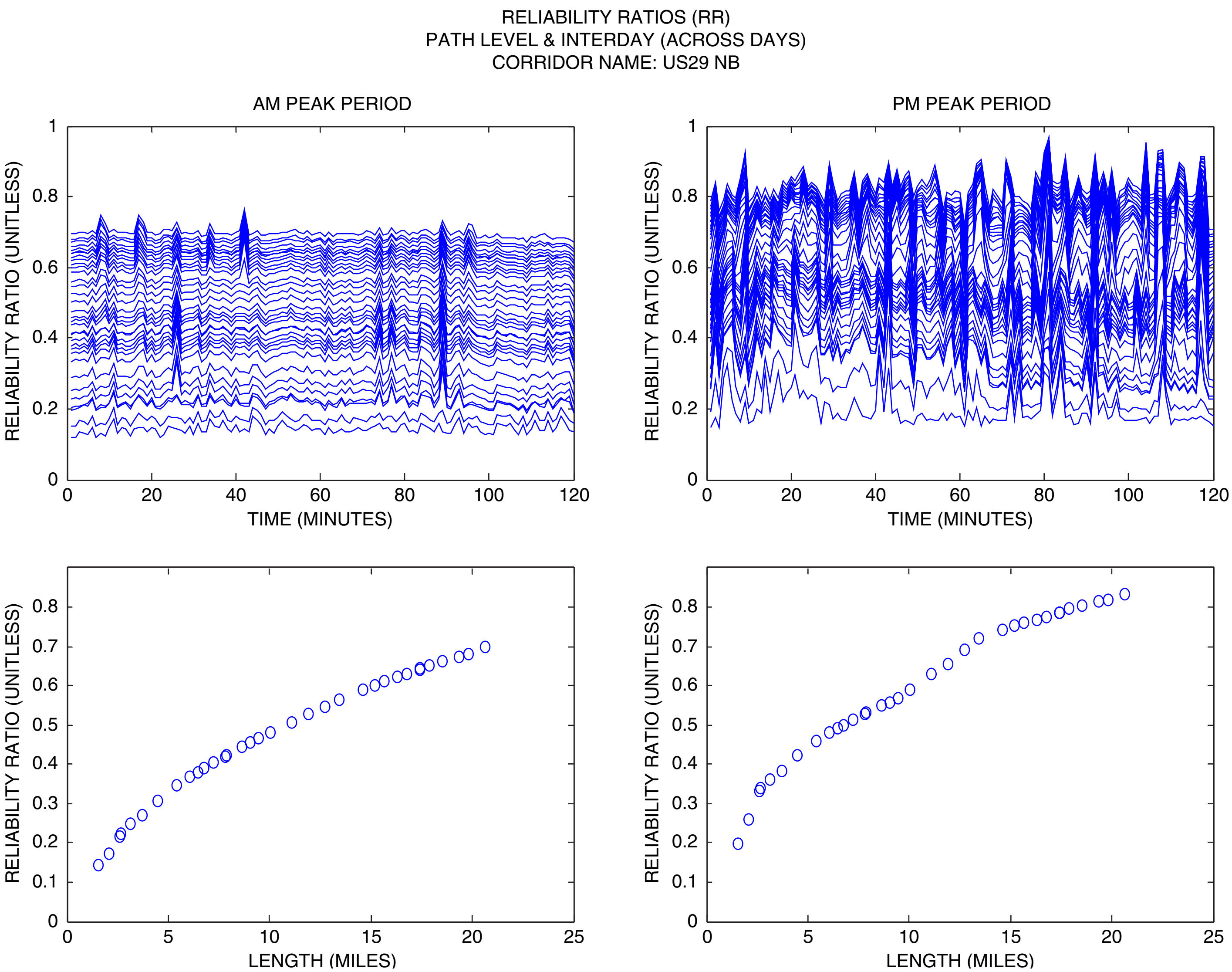


***Figure E.27. Analysis results on northbound US-29 corridor: left, AM peak period; right, PM peak period; top, reliability ratio over time; and bottom, average reliability ratio versus length.***

*Table E.11. TMC Segment Definitions on Southbound US-29 Corridor*

| TMC | Roadnumber | Firstname | County | Direction | Miles |
|---|---|---|---|---|---|
| 110N05252 | US-29 | I-70 | HOWARD | SOUTHBOUND | 0.868904 |
| 110-05251 | US-29 | US-40 | HOWARD | SOUTHBOUND | 0.629913 |
| 110N05251 | US-29 | US-40 | HOWARD | SOUTHBOUND | 0.59207 |
| 110-05250 | US-29 | MD-103 | HOWARD | SOUTHBOUND | 0.729959 |
| 110N05250 | US-29 | MD-103 | HOWARD | SOUTHBOUND | 0.529495 |
| 110-05249 | US-29 | MD-100/Exit 22 | HOWARD | SOUTHBOUND | 0.027342 |
| 110N05249 | US-29 | MD-100/Exit 22 | HOWARD | SOUTHBOUND | 0.651041 |
| 110-05248 | US-29 | MD-108 | HOWARD | SOUTHBOUND | 0.478789 |
| 110N05248 | US-29 | MD-108 | HOWARD | SOUTHBOUND | 0.563983 |
| 110-05247 | US-29 | MD-175 | HOWARD | SOUTHBOUND | 0.355254 |
| 110N05247 | US-29 | MD-175 | HOWARD | SOUTHBOUND | 0.764136 |
| 110-05246 | US-29 | Brokenland Pkwy/Exit 18 | HOWARD | SOUTHBOUND | 1.297297 |
| 110N05246 | US-29 | Brokenland Pkwy/Exit 18 | HOWARD | SOUTHBOUND | 0.462197 |
| 110-05245 | US-29 | MD-32/Exit 16 | HOWARD | SOUTHBOUND | 0.866977 |
| 110N05245 | US-29 | MD-32/Exit 16 | HOWARD | SOUTHBOUND | 0.905442 |
| 110-05244 | US-29 | Johns Hopkins Rd/Exit 15 | HOWARD | SOUTHBOUND | 0.941483 |
| 110N05244 | US-29 | Johns Hopkins Rd/Exit 15 | HOWARD | SOUTHBOUND | 0.724801 |
| 110-05243 | US-29 | MD-216 | HOWARD | SOUTHBOUND | 0.76165 |
| 110N05243 | US-29 | MD-216 | HOWARD | SOUTHBOUND | 0.383777 |
| 110-05242 | US-29 | Old Columbia Rd | HOWARD | SOUTHBOUND | 0.250114 |
| 110N05242 | US-29 | Old Columbia Rd | HOWARD | SOUTHBOUND | 0.095447 |
| 110-05241 | US-29 | Howard/Montgomery County Line | HOWARD | SOUTHBOUND | 0.645697 |
| 110-06887 | US-29 | Dustin Rd | MONTGOMERY | SOUTHBOUND | 0.419569 |
| 110N06887 | US-29 | Dustin Rd | MONTGOMERY | SOUTHBOUND | 0.360847 |
| 110-05902 | US-29 | MD-198/Sandy Spring Rd | MONTGOMERY | SOUTHBOUND | 0.422428 |
| 110N05902 | US-29 | MD-198/Sandy Spring Rd | MONTGOMERY | SOUTHBOUND | 0.296843 |
| 110-05901 | US-29 | Greencastle Rd | MONTGOMERY | SOUTHBOUND | 1.23379 |
| 110-05900 | US-29 | Briggs Chaney Rd | MONTGOMERY | SOUTHBOUND | 0.788743 |
| 110N05900 | US-29 | Briggs Chaney Rd | MONTGOMERY | SOUTHBOUND | 0.273789 |
| 110-05899 | US-29 | Fairland Rd | MONTGOMERY | SOUTHBOUND | 0.705289 |
| 110N05899 | US-29 | Fairland Rd | MONTGOMERY | SOUTHBOUND | 0.032313 |
| 110-05898 | US-29 | Cherry Hill Rd/Randolph Rd | MONTGOMERY | SOUTHBOUND | 0.596233 |
| 110N05898 | US-29 | Cherry Hill Rd/Randolph Rd | MONTGOMERY | SOUTHBOUND | 0.564728 |
| 110-05897 | US-29 | MD-650/New Hampshire Ave | MONTGOMERY | SOUTHBOUND | 1.555923 |

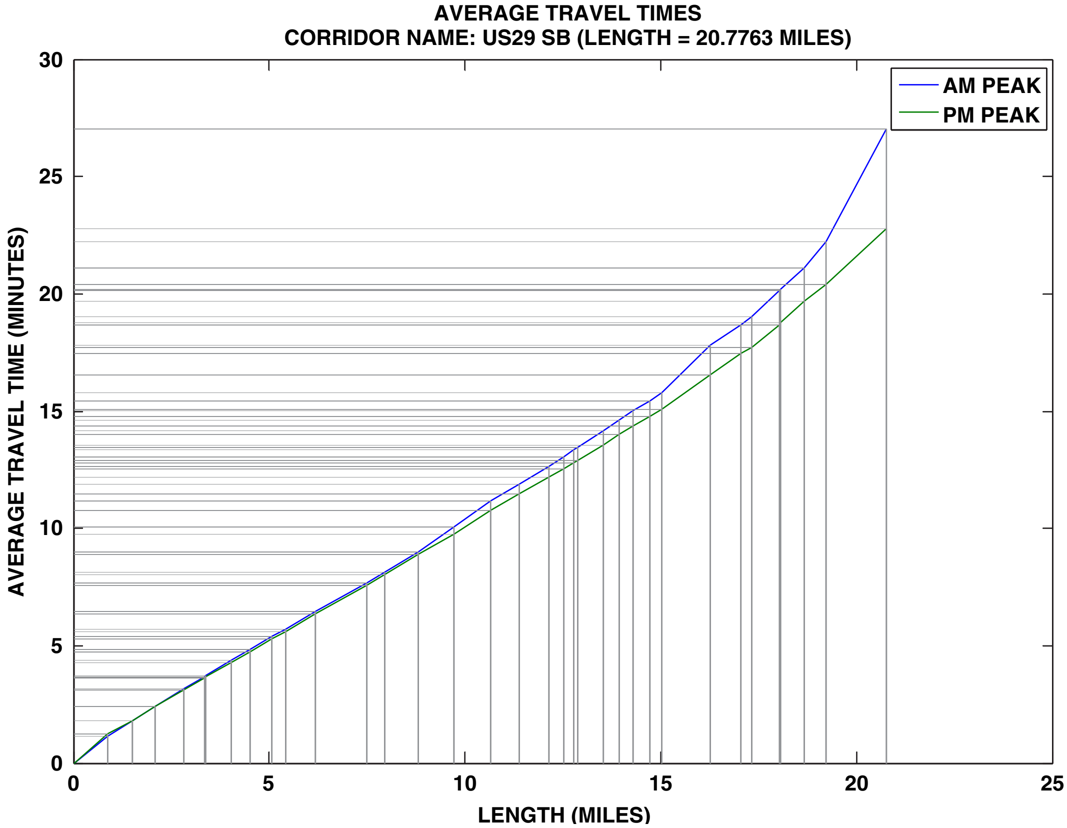


*Figure E.28. Average travel time versus length on southbound US-29 corridor.*

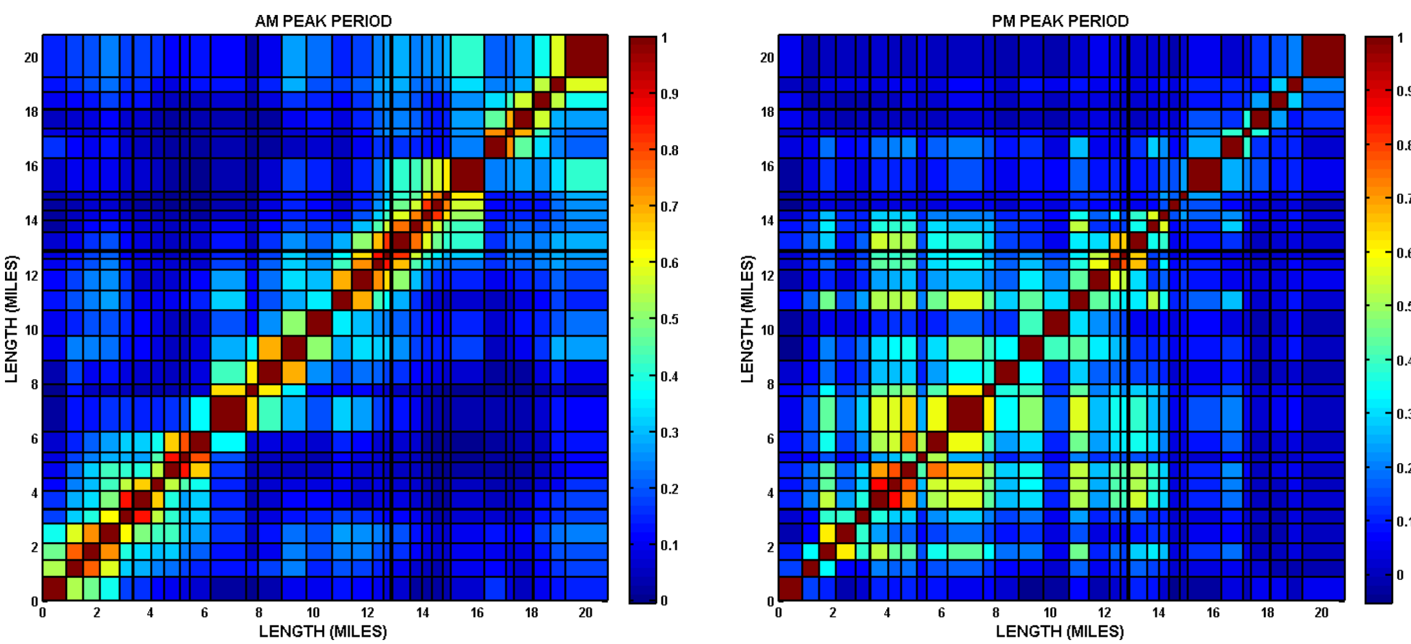


*Figure E.29. Travel time correlations on southbound US-29 corridor: left, AM peak period; right, PM peak period.*

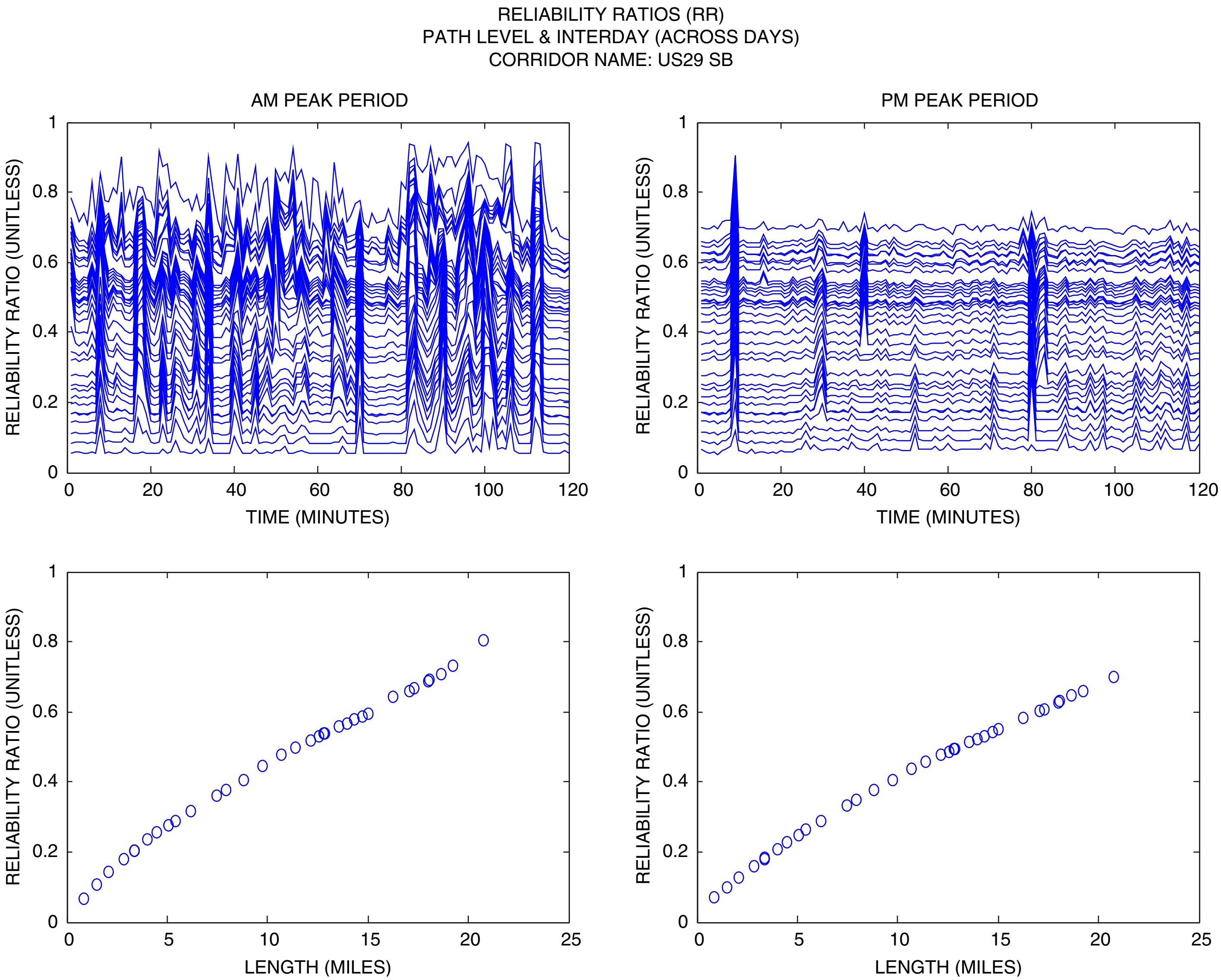


***Figure E.30. Analysis results on southbound US-29 corridor: left, AM peak period; right, PM peak period; top, reliability ratio over time; and bottom, average reliability ratio versus length.***

## Related SHRP 2 Research

Incorporating Reliability Performance Measures into Operations and Planning Modeling Tools (L04)

Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes (L05)

Identification and Evaluation of the Cost-Effectiveness of Highway Design Features to Reduce Nonrecurrent Congestion (L07)

Evaluating Alternative Operations Strategies to Improve Travel Time Reliability (L11)

Value of Travel Time Reliability in Transportation Decision Making: Proof of Concept—Portland, Oregon, Metro (L35A)

Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand (C04)