Estimation and Valuation of Travel Time Reliability for Transportation Planning Applications

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ABSTRACT

This paper proposes a method to measure the value, forecast, and incorporate reliability in the transportation planning process. Empirically observed travel time data from INRIX are used in an introduced method to measure Origin Destination (OD)-based reliability. OD-based reliability is a valuable concept, since it can be easily incorporated in most travel models. The measured reliability is utilized to find the value of reliability for a specific mode choice problem and to establish the relationship between travel time and reliability. This relationship is useful to forecast reliability in future scenarios. Findings are combined with Maryland Statewide Transportation Model to find the value of reliability savings by improving the network in a case study. The Inter-County Connector is used as the case study to show the significance of reliability savings. The proposed approach can be used to (1) provide a systematic approach to estimate travel time reliability for planning agencies, (2) incorporate travel time reliability in transportation planning models, and (3) evaluate reliability improvements gained from transportation network investments.

Keywords: reliability; transportation planning; travel time; mode choice; network investments

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ABSTRACT

This paper proposes a method to measure the value, forecast, and incorporate reliability in the transportation planning process. Empirically observed travel time data from INRIX are used in an introduced method to measure Origin Destination (OD)-based reliability. OD-based reliability is a valuable concept, since it can be easily incorporated in most travel models. The measured reliability is utilized to find the value of reliability for a specific mode choice problem and to establish the relationship between travel time and reliability. This relationship is useful to forecast reliability in future scenarios. Findings are combined with Maryland Statewide Transportation Model to find the value of reliability savings by improving the network in a case study. The Inter-County Connector is used as the case study to show the significance of reliability savings. The proposed approach can be used to (1) provide a systematic approach to estimate travel time reliability for planning agencies, (2) incorporate travel time reliability in transportation planning models, and (3) evaluate reliability improvements gained from transportation network investments.

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INTRODUCTION

An appropriate travel demand model is expected to predict travelers' choices with adequate accuracy. These choices primarily consist of departure time choice, mode choice, path choice and en-path diversion choice. Unpredictable variation in travel times of a specific mode, path, or time is one of the most important attributes considered by travelers. Travel time reliability (TTR) is defined as "the consistency or dependability in travel times, as measured from day-to-day and/or across different times of the day" (FHWA 2009). The concept of TTR has been raised and employed in different studies to define and measure this unpredictable variation of travel time. According to Bhat and Sardesai (Bhat and Sardesai 2006), travelers consider reliability for two main reasons. First, commuters may be faced with timing requirements, and there are consequences associated with early or late arrival. Second, they inherently feel uncomfortable with unreliability because it brings worry and pressure. This behavioral consideration has been noted in many studies where it is observed that some travelers accept longer travel times in order to make their trip more reliable (Jackson and Jucker 1982).

Reliability has become a significant part of travel models since early studies (Gaver Jr 1968; Prashker 1979). Many theoretical and experimental studies have considered reliability in their departure time choice, path choice or mode choice models, using stated preference (SP) or revealed preference (RP) surveys. While SP surveys describe a hypothetical situation for respondents, RP surveys ask about their actual choice and do not contain usual perception errors found in SP surveys. While there are a number of reliability studies using SP surveys, there are few studies that utilize RP surveys due to the lack of experimental settings that have significant differences among alternatives, and hardships in planning and deploying these surveys and gathering the data (Carrion and Levinson 2012). Bates et al. (Bates et al. 2001) claimed it was virtually impossible to find RP situations with sufficient perceived variation in reliability and other appropriately compensating components of journey utility. Although there are some good examples of departure time choice and path choice research using RP surveys (Carrion and Levinson 2010, 2012; Lam and Small 2001; Small 1992), they all analyze TTR in link-level or path-level. There is no previous study about Origin-Destination (OD)-level TTR, even though OD level studies are extensively used in the literature (Alam 2009; Alam et al. 2010; Raphael 1998; Thompson 1998). Since trip-based and activity-based travel demand analysis and modeling are usually conducted at the zone level, OD-level TTR measure would be of great value in incorporating reliability into current planning process.

The main contribution of this study is introducing an OD-based reliability approach on empirically observed data to be used in planning process. OD-based reliability is important because it can easily be incorporated in planning processes or travel models. Additionally, reliability and its value are measured and estimated using empirically observed travel times and household travel surveys, which can be easily available. This is very valuable since conducting new SP surveys for reliability is costly, and estimates based on SP surveys contain perception errors. The objective of this paper is to develop a framework to (1) measure travel time reliability, (2) determine the value of reliability, (3) incorporate reliability in transportation planning models, and (4) estimate changes in reliability because of new or proposed transportation infrastructure investments. This paper discusses various steps on how to consider reliability as a performance measure in planning and the decision-making process by making the best utilization of available data sources and planning models. Its application is also demonstrated in a real-world case study.

The remainder of the paper is organized as follows. In the next section, literature review of reliability estimation is presented, followed by a suggested methodology that can be easily adapted by planning agencies. The case study section describes application of the proposed methodology in a real world planning model. The result section discusses the importance of considering VoTR in the planning process. The conclusion section summarizes the proposed research and discusses future directions.

LITERATURE REVIEW

To date a number of studies and research papers have been published, where the value of reliability was measured using SP survey, RP survey, corridor travel times, and an assessment of the impact of reliability in demand (trip based or activity based) and capacity (network cost based) models. In the review presented herein, literature is classified in four groups (1) reliability in travel demand models, (2) data sources used for modeling reliability, (3) valuation of travel time reliability, and (4) reliability application and performance measures.

Reliability in Travel Demand Models

Reliability was introduced to travel models in early studies. Gaver Jr (Gaver Jr 1968) proposed a departure time choice model and mentioned that travelers predict variance of their travel time and depart with a safety margin, which he called “Head start time”. Polak (Polak 1987) stated that reliability should be an explicit term in the models, and added a reliability variable to a mode choice model, which showed statistically significant improvement. The path choice model developed by Jackson and Juker (Jackson and Jucker 1982) can be considered as the first study that utilized expected utility theory and the concept of reliability together. Jackson and Juker (Jackson and Jucker 1982) stated that travel time unreliability is a source of disutility in addition to travel time, and used a SP survey to assess the respondents’ tradeoffs between travel time and reliability, and also calculated user’s degree of risk aversion. The same method is used in other studies but with a different form of utility function (Polak 1987; Senna 1994). Reliability has also gone through network traffic equilibrium models where Mirchandani and Soroush (Mirchandani and Soroush 1987) incorporated travel time variance in the utility function, and showed how users shifted their path to more reliable ones.

It is clear that reliability is an important measure of the health of the transportation system in a region, as state Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs) prepare to manage, operate and plan for future improvements. Travel time reliability, depicted in the form of descriptive statistics derived from the distribution of travel times is a critical indication of the operating conditions of any road. Considering its importance, transportation planners are inclined to include reliability as a performance measure to alleviate congestion. To investigate the use of travel time reliability in transportation planning, Lyman and Bertini (Lyman and Bertini 2008) analyzed twenty Regional Transportation Plans (RTPs) of metropolitan planning organizations (MPOs) in the U.S. None of the RTPs used reliability in a comprehensive way, though a few mentioned goals of improving regional travel time reliability. Even though many studies have tried to measure behavioral response to reliability, their application in a transportation-planning context is limited. Studies were conducted to understand the reliability of specific paths (Chen et al. 2003; Levinson 2003; Liu et al. 2004; Tilahun and Levinson 2010). Specifically, reliability measures are studied for freeway corridors through empirical analysis and simulation approaches were also applied (Chen et al. 2000; Levinson et al. 2004; Rakha et al. 2006; Sumalee and Watling 2008; Zhang 2012). However, freeway corridors only encompass a portion of a real-life multimodal transportation network. A planning agency trying to evaluate the effect of various policies (other than freeways) may not be able to fully utilize such information to estimate the value of travel-time reliability savings on an overall network level. In the planning stage, agencies often are not ready to collect new data, but would like to utilize available resources to estimate travel time reliability using existing tools such as using the travel demand model; Hence, a framework to measure OD-based reliability to calculate network-wide reliability savings using available data will be very useful, and is currently lacking in the literature.

Data Sources for Modeling Reliability

Data for reliability studies are usually obtained from surveys. Qualitative questionnaires were the first surveys used in reliability studies where respondents were asked to rank the foremost reasons of their path choice, including some reasons that were related to reliability (Chang and Stopher 1981; Prashker 1979; Vaziri and Lam 1983). Then, gradually quantitative SP surveys became dominant in the field and were utilized in numerous studies (Abdel-Aty et al. 1997; Jackson and Jucker 1982) is one example. In a path choice study, Abdel-Aty et al. (Abdel-Aty et al. 1997) offered two paths to the respondents; one with fixed travel time every day, and the other with a possibility that the travel time increases on some day(s). The results showed that males are more willing to choose uncertain paths. In the scheduling study of Small (Small 1999), respondents were given two options with different travel time distributions and travel costs based on their preferred arrival time. Small (Small 1999) found that unreliability had higher disutility for respondents with children and respondents with higher income. Some other studies (Koskenoja 1996; Small et al. 2005) added nonlinearities in the scheduling models. SP surveys evolved later (Bates et al. 2001; Cook et al. 1999) showed how the presentation of travel time variability can have a significant impact on the estimation; their work was followed in different reliability studies (Asensio and Matas 2008; Copley and Murphy 2002; Hensher 2001; Hollander 2006; Tilahun and Levinson 2010). While there are many examples of reliability studies using SP data in the literature, RP studies are limited. Carrion and Levinson (2012) related this scarcity to a lack of experimental settings showing significant difference among alternatives and costs associated with planning, deploying and gathering data from these surveys (Carrion and Levinson 2012).

Valuation of Travel Time Reliability

Value of Travel Time (VoT) and Value of Travel Time Reliability (VoTR) are two important parameters used in transportation planning and travel demand studies. VoT refers to the monetary value travelers place on reducing their travel time. Similarly, VoTR denotes the monetary value travelers place on reducing the variability of their travel time or improving the predictability. Over the years, VoT has a long established history through the formulation of time allocation models from a consumer theory background (Jara-Díaz 2007; Mishra et al. 2014; Mishra and Welch 2012; Small and Verhoef 2007; Welch and Mishra 2013, 2014). Various models and their review in the mainstream of travel demand modeling are thoroughly discussed in the literature (Abrantes and Wardman 2011; Shires and de Jong 2009; Zamparini and Reggiani 2007). In contrast, VoTR has been gaining significant attention in the field. However, despite increased attention, the procedures for quantifying it are still a topic of debate, and a number of researchers and practitioners have proposed numerous aspects, such as: experimental design (e.g. presentation of reliability to the public in stated preference (SP) investigations); theoretical framework (e.g. scheduling vs. centrality-dispersion); variability (unreliability) measures (e.g. interquartile range, standard deviation; a requirement in the centrality-dispersion framework); data source (e.g. RP vs. SP); and others (Carrion and Levinson 2012; Koppelman 2013; Mahmassani et al. 2013; Shams et al. 2017). As a consequence, VoTR estimates exhibit a significant variation across studies.

Reliability Application and Performance Measures

Some of the applications of reliability include path choice studies for State Route 91 (Small et al. 2005, 2006), High Occupancy Toll lanes in Interstate 15, San Diego (Ghosh 2001), travelers' path choice between an un-tolled lane, a tolled lane and a signalized arterial parallel to them in Minneapolis (Carrion and Levinson 2010), ranking of recurring bottlenecks at the network level (Linfeng and Wei (David), Fan 2017), prediction of future traffic conditions using GPS data (Wang et al. 2017), freeway travel time using radar sensor data (Lu and Dong 2017), travel time reliability in developing country conditions using Bluetooth sensors(Mathew et al. 2016), congestion measures during disasters (Faturechi Reza and Miller-Hooks Elise 2015), and a bridge choice model using GPS data for Interstate 35W (Carrion and Levinson 2012). Some of the initial performance measures of reliability were percent variation, misery index and buffer time index (Lomax et al. 2003). In subsequent studies by the Federal Highway Administration and in the National Cooperative Highway Research Program (NCHRP), 90th or 95th percentile travel time, buffer index, planning time index, percent variation, percent on-time arrival and misery index are recommended as travel time reliability measures (Systematics 2008). Pu (2011) compared various measures of travel time reliability and suggested that standard deviation as a robust estimate. Recent Strategic Highway Research Program research recommended a list of five reliability measures similar to those found in the NCHRP report, with skew statistic replacing the percent variation (Systematics 2013). Liang et al. (Liang et al. 2015) studied the impacted of travel time reliability in travelers' mode choice decision and built models using three reliability measures: standard deviation, 90th minus 50th percentile of travel time and 80th minus 50th percentile of travel time. The three reliability measures were all able to capture the effect of travel time reliability in travelers' mode choice and were similar in performance.

Summary of Literature Review

In reviewing previous literature, it is evident that a model using a reliable source of travel-time measurement data supplementing a RP survey (e.g. household travel survey) for TTR that can be utilized in planning process is not available in the literature. Besides, none of the studies have considered OD-based TTR. By using probe and individual vehicle travel time data, TTR estimation can be significantly improved. In this paper, empirically observed travel time data are used to estimate OD-based level TTR measures. The OD level TTR measures are combined in a household travel survey to provide a comprehensive RP dataset, which is used to develop discrete choice models to obtain the value of reliability. The reliability data are combined with travel time data to explore the relationship between travel time and travel time reliability in order to forecast the reliability. All these findings are combined in a travel demand model to demonstrate how OD-based reliability can be incorporated in planning and decision making. In the next section, we describe the proposed methodology.

METHODOLOGY

While origin-destination-based shortest path travel time is available from number of sources, path-based reliability is not readily available. The “Observed TT Data” part of the framework shown in the middle rectangle of Figure 1 utilizes observed travel time data to capture path-based reliability. The reliability data obtained from this part are combined with the socio-demographic variables in “Random Utility Model” part of framework shown in the left rectangle where a random utility choice model (an example could be mode choice) is developed in order to find Value of Reliability. Path-based reliability and travel time data obtained in “Observed TT Data” part are also used to develop a relationship between travel time and travel time reliability. This relationship is essential since planning models usually output travel times, but reliability data is not reported. Finally, the Value of reliability and Reliability-Travel time relationship are used in the “planning model” part of the framework to obtain value travel time reliability savings in a transportation planning or travel demand model, which is the final goal of this paper. Each part of the framework is explained in greater detail later in the paper.

Reliability and Mode Choice

The first task is to identify the population of travelers with desired origins, destinations, and activity times reflecting their daily activity schedules and recognize network of links and nodes representing the study area. Typically, this information is obtained in a regional Household Travel Survey (HHTS) or any RP survey. The survey would provide the activity-scheduling process, containing trips with known origins, destinations, and departure times. Given a time-varying network $G = (N, A)$, where N is a finite set of nodes and A is a finite set of directed links, the time period of interest is discretized into a set of small time intervals. The time-dependent zonal demand represents the number of individual travelers of an Origin-Destination (OD) pair q $(q \in Q)$ at departure time t $(t \in T)$, *choosing path* r $(r \in R)$. The set of available modes are denoted as *M* ($m \in M$). A key behavioral assumption for the mode choice decision is that in a random utility maximization framework, where each traveler chooses a mode that maximizes his or her perceived utility. With no loss of generality, the choice probability of each mode can be given by

$$U(m) = \alpha TT^{qt}_{r,m} + \beta TC^{qt}_{r,m} + \gamma TTR^{qt}_{r,m} + \theta_i DC_i + \in, \forall r \in R(q,t,m) \tag{1}$$

Where,
TT = path travel time
TC = Travel cost
TTR = Travel time reliability (example: coefficient of variation)
DCi = Decision maker's <u>*ith*</u> characteristics
α = coefficient of travel time
β = coefficient of travel cost
γ = coefficient of reliability
θ_i= coefficient of decision maker's *ith* characteristic
α / β = value of time
γ / β = value of travel time reliability
γ / α =reliability ratio

The mode choice model provides the relative fractions of users of different modes, including those whose choices entail automobile use as driver or passenger on the transportation network. In the case study, the mode choice model between driving and rail is considered. The main features of the problem addressed here entail the response of users not only to attributes of the travel time experienced on average by travelers on a particular path at a given time, but also to the prices or tolls encountered and the reliability of travel time. Accordingly, users are assumed to choose a path that minimizes a generalized cost or disutility that includes three main path attributes: travel time, monetary cost, and a measure of variability to capture reliability of travel. In the above generalized cost expression, the parameters α and β represent individual trip maker's preferences in the valuation of the corresponding attributes. The preferences vary across travelers in systematic ways that may be captured through user socio demographic or trip-related attributes (variable *DCi*) or in ways that may not be directly observable. To realistically capture the effect of reliability on different user groups (heterogeneity), it is essential to represent the variation of user preferences in response to cost in each mode, captured here through the parameter α. Accordingly, the focus is on capturing heterogeneous VoT preferences across the population of highway users. Preferences for reliability may also reflect heterogeneity, and the same approach used here for VOT may be extended to incorporate both.

<<Figure 1 Here>>

Estimating Reliability Measure

The first task would be to obtain travel time data for a region on selected OD pairs. The travel time data could be of two types: (1) designed path travel times, and (2) variation on travel times. The travel time variation should capture the actual travel times taken by the vehicles. A relationship between travel time and travel time reliability must be developed. This relationship is needed because in regional planning models, a typical day path travel time is reported and variation cannot be captured. In another study, we used the impact of travel time reliability in travelers' mode choice decision and built models using three reliability measures: standard deviation, 90th minus 50th percentile of travel time and 80th minus 50th percentile of travel time (Tanget al. 2015). The three reliability measures were all able to capture the effect of travel time reliability in travelers' mode choice and were similar in performance. In this study, we consider standard deviation as the reliability measure as it is suggested to be a robust estimate (Pu 2011), but other reliability measures should also work like 90th minus 50th percentile of travel time or 80th minus 50th percentile of travel time. Further research needs to be done to see the effect of using other reliability measures like buffer index, planning time index, percent variation. While establishing reliability measure, it would be important to describe all origins and destinations and pick the shortest path between each OD pair to estimate travel times. For capturing travel time variation, one year (or similar time frame) travel time data for the study region should be collected. An appropriate time period should be defined (say, minute by minute travel times in AM or PM hour), and the times on pre-defined paths need to be estimated as described in the case study. TTR estimation for this paper is discussed in "Case Study" section under "Measuring OD-based reliability. A relationship (such as multiple regression or similar technique) between mean travel time and travel time variation can be established. How this relationship will be useful is described in the next section.

Estimating VoTR and integration in planning models

VoTR can be estimated using any random utility model with a variable indicating reliability and travel time. In this paper we use mode choice model as an example. From the mode choice estimation VoTR can be determined as the ratio of coefficient of reliability and travel cost (γ / β). In planning models OD based travel times are considered, but not their variations. Without considering variation of travel times, the reliability of travel times is often not represented in planning models." To capture variation and to obtain reliability of each path the relationship mentioned in the previous step will be useful here. For each OD pair, reliability measure can be determined using the regression relationship between mean travel time and reliability. Once the reliability of the path is known for before and after improvement, then the savings in reliability can be computed as the demand is known for the before and after scenario.

DATA

A number of data sources are collected including (1) Household travel survey, (2) path travel times, and (3) statewide and MPO travel demand models. Each of these data sets is explained below.

Household Travel Survey

The 2007/2008 Transportation Planning Board- Baltimore Metropolitan Council Household Travel Survey is used in the paper for mode choice modeling. This survey contains four types of information which include person characteristics, household characteristics, trip characteristics and vehicle characteristics. The dataset contains 108,111 trips and their details including trip start time, distance of each trip, experienced travel time of the trip, and reported mode, along with socio-economic and demographics. The socio-economic and demographic characteristics are obtained from the person, household, and vehicle characteristics of the household travel survey. Start time is used for getting the reliability of the path since reliability will vary in different times of day.

Path Travel Time

Travel time data for various paths are obtained from INRIX. Traffic Message Channels (TMCs) are the spatial units of INRIX data. In this study, INRIX historical data is obtained for a whole year in five minute increments, for specific paths and aggregated for every hour. Reliability measure (standard deviation of travel time) for each hour of the day is calculated from one-year data, as a measure of unreliability. Travel time observations that were 10 times greater than the average travel time for each segment were considered outliers, and thus excluded from the study. INRIX does not cover all the functional classes of roadways, but it contains most of the major and minor arterials, along with a full representation of freeways, interstates, and expressways.

Travel Demand Model

The Maryland Statewide Transportation Model (MSTM) is considered as the travel demand model to demonstrate the benefits of VoTR from new infrastructure investment. MSTM is a traditional four-step travel demand model that is well-calibrated and validated, and is currently being used for various policy and planning applications in Maryland. Details of the model structure is presented in the literature (Mishra et al. 2011, 2013).

In the state of Maryland majority of trips origins are destinations occur in the metropolitan areas of Baltimore and District of Columbia. Out of 24 counties in the state, 12 counties are covered by the two metropolitan areas. The remainder 12 counties are considered as mostly rural located in the eastern shore and western part of state. While automobile is the primary mode of travel, the metropolitan areas consists of extensive transit service and more than 10 percent of trips are by transit. Figure 2(a) shows the highway and transit network. The highway network consists of all major functional classes, and transit network consists of services provided by Maryland transit administration, Washington Metropolitan Area Transit Authority (WMATA), and inter-city commuter rail. Figure 2(b) shows location of all transit stops including all bus and rail services. As it is evident from the figure transit service is primarily available in the metro areas, and not in rest of the state.

To estimate reliability savings because of recent network investment, we consider the Inter County Connector (ICC) as a part of the case study. More on ICC can be found in the literature (Zhang et al. 2013). Figure 2(c) shows a detailed view of ICC along with other major facilities in the southern Maryland. ICC is one of the most significant and high-profile highway projects in Maryland since the completion of the existing Interstate freeway system several decades ago. The ICC connects existing and proposed development areas between the I-270/I-370 and I-95/US-1 corridors within central and eastern Montgomery

County and northwestern Prince George's County (the two most populous counties in Maryland). ICC opened to traffic in the year 2011. The impact of TTR and VOTR on other major facilities because of newly opened ICC is further presented in the result section.

MWCOG model is used to provide travel cost information of different modes for trips in HHTS data. Information like transit fares between zones, parking costs, and auto operating cost from MWCOG model are used to calculate travel cost for transit and driving. Since the MWCOG model shares the same zoning structure with HHTS data, the travel cost generated from MWCOG model can be easily incorporated with HHTS data.

<<Figure 2 Here>>

Scenarios Considered

To demonstrate the VoTR savings, four scenarios are developed: Base year build, base year no-build, future year build, and future year no-build. The base year build and no-build scenarios reflect ICC and other minor network improvements between 2007 and 2013. The future year build scenario consists of improvements as reported in the constrained long range plan. In the future year build scenario a number of improvements are considered, such as the I-270 expansion, I-695 expansion, a network of toll roads, purple line transit and red line transit. The future year no-build scenario considers the base year network and with future year demand (socioeconomic and demographic).

CASE STUDY

The case study section is arranged in four subsections. These subsections include (1) measuring OD-based reliability, (2) forecasting OD-based reliability, and development of a mode choice model to obtain RR, and VOTR.

Measuring OD-based Reliability

In this study, OD pairs that have both rail and driving trips recorded in Washington DC area travel survey. The rationale for selecting these OD pairs is because these OD pairs both travel modes are available and are competing with each other. In total, there were 161 OD pairs with both rail and driving trip records. In two of these OD pairs, INRIX data was not available. The rest 159 OD pairs are used for collecting INRIX data this paper to compute value of travel time reliability. To develop a mode choice model, household data was required in addition to INRIX travel time and travel time reliability data. The household socioeconomic, demographic, and travel characteristics were obtained from HHTS. From the HHTS 554 trips were found encompassing 159 OD pairs.

The INRIX travel time data is processed in five steps as shown in Figure 3. The first step constitutes identification of shortest path. In this paper Google Map is used to identify the shorted path between OD pairs and travel time is considered as the criteria for selecting shortest path. The second step obtains INRIX travel time data on the selected shortest paths. Average travel time for each hour of the day (24 values) for one year (365 days) is collected. Weekend data is deleted at this point since the respondents were required to record activities on a weekday in the HHTS. In the third step all available INRIX travel time data along the shortest path are added to calculate travel time on the shortest path for different time of day. In the fourth step, travel time calculated in step three are extended to the full path. Road segments are divided into two categories: freeway and non-freeway. Road segments belong to the same category are assumed to have similar average speed. Travel time for segments that are missing from INRIX are then estimated using available data in the same category, either freeway or non-freeway. The fifth step estimates TTR for different time of day.

<<Figure 3 Here>>

Forecasting Reliability

Typical planning models report static travel times at each time of day. They do not report the variation of travel times. The estimated OD level travel times and travel time reliabilities were used to establish the relationship between travel time and travel time reliability. This relationship is useful because it can be incorporated with OD travel time matrices to find out the OD reliability matrices. The network-wide value of reliability saving can be easily calculated using OD reliability matrices.

To establish this relationship various types of regression using different reliability measures as dependent variable, different travel time and congestion measures as independent variable, and different forms of regression were tried. Finally, standard deviation per mile which indicates amount of unreliability normalized by distance is regressed with percent deviation of congested travel time from free flow travel time. The regression model uses all 159 collected OD pairs' data. Each OD pair, has 24 data points regarding reliability and congestion measure of each hour, which sums up to 3816 data points. A number of outliers were removed from the regression estimation. The Logarithmic relationship was found to provide the best goodness of fit. The parameters are estimated using non-linear least square approach, and the result is shown in Figure 4. The resulting r-square is 0.7675. This relationship will be used to find the change in reliability for any two given scenarios to calculate reliability savings.

<<Figure 4 Here>>

Development of a Mode Choice Model

Drivers tend to dislike high travel time variations because of various reasons, such as accidents, bad weather, roadwork, fluctuation in demand, etc. On the other hand, rail usually has much more reliable travel times since it operates following a fixed schedule. So it would be interesting to explore how this difference in TTR would affect traveler's choice between these two modes. In this study, OD pairs that have both rail and driving trips recorded in 2007-2008 travel survey in Washington, D.C., area are selected and studied since in these OD pairs both travel modes are available and are competing with each other. In these 159 OD pairs, 261 rail trips, 291 driving trips, and only 2 trips of other travel modes can be observed, as shown in Table 1. Thus, in these OD pairs, it would be appropriate to assume that rail and driving are the only available alternatives.

<<Table 1 Here>>

Explanatory variables used in the mode choice model are shown in Table 2. Travel cost information is provided by MWCOG model. Travel time reliability for driving is calculated from INRIX data, while rail is assumed to be highly reliable and has no variation in travel time. Other information comes from HHTS data. The travel time of driving and transit is estimated by averaging the reported travel time of all the trips in the same OD pair using that mode.

<<Table 2 Here>>

The model specification adopted in this paper is shown below:

$$U_d = \beta_0 + \beta_{veh} * Veh + \beta_{age} * Age + \beta_{disc} * Disc + \beta_{TT} * TT_d + \beta_{cost} * Cost_d + \beta_{TTR} * TTR + \varepsilon_d \tag{2}$$

$$U_r = \beta_{TT} * TT_r + \beta_{cost} * Cost_r + \varepsilon_r \tag{3}$$

where U_d is the utility of driving and U_r is the utility of rail. *Veh*, *Age* and *Disc* are explained in Table 2. TT_d *and* TT_r denote travel time for driving and rail. $Cost_d$ *and* $Cost_r$ represent travel cost for driving and rail. *TTR* is the TTR for driving. β_0 denotes mode-specific constant. β_{Veh}, β_{Age}, β_{TT}, β_{Cost}, β_{TTR} are coefficients for corresponding explanatory variables.

Based on the model specification, value of reliability (VOR) can be calculated:

$$VoR = \frac{\beta_{TTR}}{\beta_{cost}} \tag{4}$$

Reliability ratio (RR) can be calculated by using VOR divided by value of time (VOT):

$$RR = \frac{VOR}{VOT} \tag{5}$$

The results of two mode choice models are shown in Table 3. Travel time reliability is not included in the first model. Since driving is not a possible choice for people without a driver license, those trips are not included in the model. This consideration excludes 32 trips.

<<Table 3 Here>>

Based on the results, the coefficients of the variables Household Vehicles, Age of the Driver, and Discretionary Trips are significant with positive sign, which means that older people owning more cars tend to drive more. Besides, people will drive more for discretionary trips. The coefficients of Travel Time and Travel Cost are negative, which shows that people will drive less if driving will take longer or cost more compared to rail. Travel Time is not significant, which may be caused by the method of how travel time is calculated. As described earlier, travel time of the alternative mode is estimated by averaging the reported travel time of all the trips in the same OD pair using that mode. However, there is a gap between the calculated travel time and the real travel time, which may lead to the insignificance of travel time in the model.

In the second model, the coefficient of the TTR variables is significantly negative, which shows that people tend to drive less when travel time variation of driving increases. The value of travel time reliability (VOR) and its 95 percent confidence interval (CI) are also calculated and shown in Table 3. Based on MSTM, the average value of time in Maryland is $14/hour. The RR can then be estimated using VOR divided by VOT, which is 4.02. It is larger than RRs in the previous literature which usually vary from 0.10~ 2.51 (Carrion and Levinson 2012a) This may be caused by several reasons. First of all, reported travel times in the survey do not show a significant difference between rail and auto. But in reality, rail has longer travel time with higher reliability. This is the reason why the model relates auto travels to lower cost of auto, and relates rail travels to higher reliability of rail; but it cannot find a significant effect of travel time, because travel time is not significantly different between alternatives. As a result, travel time becomes insignificant, and value of time is estimated to be very low. Second, the mode choice model in this study only considers rail and driving, while other modes exist in reality, such as bus, carpool or bike. Third, TTR in this study is calculated by user-experienced data in the Washington, D.C., area. Instead, most previous studies used SP survey to collect reliability information. The use of SP and RP data often cause different estimations (Ghosh 2001). Moreover, the use of different time intervals will lead to different travel time variations. Since a 1-hour time interval is used in this study for reliability, the TTR measures estimated will be much lower than using smaller time intervals, thus leading to a higher estimation of reliability ratio. Finally, different reliability measures will lead to different RR estimations. For these reasons, the RR value may vary a lot when using different reliability measures or different estimation methods.

RESULTS AND DISCUSSION

The results presented are for four scenarios and two planning years. The four scenarios include base year build, base year no-build, future year build, and future year no-build, and two planning years include 2010 (base year), and 2030 (future year). Travel time savings and travel time reliability savings are computed for base year and future year. For comparison, average travel time by OD pair and by time of day before and after system enhancement are captured. Then the system benefits are estimated resulting from improved travel reliability. The base year comparison shows benefits because of ICC, and the future year comparison will show benefits resulted from the projects included in long range plan. The findings are summarized at varying geographic levels: statewide, county, zone and corridor. The statewide, county and zone refers to corresponding geographic boundaries of the state, individual counties and traffic analysis zones. However, a corridor refers to specific segment of a roadway section in the transportation network. The size of the origin destination matrix changes while computing travel time and travel time reliability savings at state, county and zone level. For example, at the state level, the statewide OD matrix is used, while at the county level the size of the OD matrix is smaller than the state and corresponds to the geographic boundaries of the county. Similarly, at zone level, the size of the OD matrix consists of one row as origin and rest of the zones as columns referring destinations. At the corridor level, we consider the shortest path between two zones that possibly use the specific corridor of interest. Both travel time savings and travel time reliability savings are computed at these geographic levels for all four scenarios considering AM peak period only.

Statewide Findings

Statewide findings are estimated by taking travel time improvements for all OD pairs when multiplied by corresponding trips. Findings suggest that both base and future year cases receive savings when compared to their no-build counterparts (Table 4). Future year savings are higher than base year, as expected. At the statewide level, travel-time reliability savings are approximately ten percent that of travel time for base year. Table 4 shows statewide travel time and travel time reliability savings for a typical AM peak hour. It is expected that the future year will have larger savings because of a greater number of new projects introduced in the long range plan.

<<Table 4 Here>>

County Level Findings

Travel time savings for the base and future years are shown in Figure 5(a), and travel time reliability savings are plotted at the county level in Figure 5(b). County level savings are shown for a typical day in AM peak period. In the base year, Montgomery and Prince George’s county received higher savings. These savings are because of ICC in the base year build scenario. In the future year, Anne Arundel and Baltimore counties received higher savings, as justified by constrained long-range plan projects in these counties.

<<Figure 5 Here>>

Corridor Level Findings

Base and future year path travel times between specific OD pair in the two ends of various corridors are considered in the reliability estimation. Travel time reliability savings are estimated for six corridors: I-270, I-95, I-495, I-695, ICC, and Purple line. The results shown in Figure 6 suggests that the travel time reliability savings are higher in the peak direction compared to off-peak direction. Among six corridors considered, ICC and purple line corridor shows higher reliability savings. When reliability savings are computed for all the travelers using these corridors for all time periods of the day and for a planning period of 20 to 30 years, such savings would be substantial to be used in the decision-making process.

<<Figure 6 Here>>

CONCLUSIONS

Reliability is a major parameter that describes the performance of transportation network. When the current condition of the network is being monitored, reliability should be among performance measures, because travelers value reliability, and consider it in their choices. In addition, when benefits and costs of proposed or current projects are being evaluated, reliability should not be neglected, since the value of reliability savings can affect the results. In this paper, a framework was proposed to measure the value, forecast, and incorporate reliability in the transportation planning process. Measuring reliability of trips between OD pairs was done using empirically observed historical data. Some assumptions (see measuring OD-based reliability sub-section for details) made it possible to convert link travel times into OD travel times, and standard deviation of travel time was calculated using between day variations of the data as a reliability measure. OD-based reliability introduced in the paper is useful and important, because it can be easily incorporated in travel models. Afterward, these data were used to estimate a mode choice model between two competing alternatives with reliability as an independent variable. The estimated coefficient of reliability made it possible to find reliability ratio and value of travel time reliability (RR and VoTR). This value is unique, since it is based on empirically observed OD-based reliability in mode choice context. The reliability data were also combined with travel time data to obtain the relationship between travel time and travel time reliability. A nonlinear regression was used to regress travel time reliability on travel time. This regression was useful for obtaining reliability matrices when travel time matrices are available. These findings were combined with MSTM in four different scenarios to find the economic benefits of building ICC in the base year, and some more extensive network improvements in the future year. Value of reliability savings by these improvements was calculated and presented in four different levels; state, county, zone, and corridor level.

The case study findings showed a considerable amount of reliability savings that should not be neglected. State level findings illustrated that reliability savings were about 10 percent of travel time savings. It also displayed that more comprehensive improvements in year 2030 will result in a larger value of reliability savings. County level results demonstrated that counties that benefit from network improvements also have higher reliability savings. Counties with the highest reliability savings showed to be different between a base year and future year due to the geographical pattern of network improvements. Zone level results displayed that future savings are more spread out in the state. Corridor level findings demonstrated considerable value of reliability savings per traveler for some major corridors. The results in different levels suggested that reliability should not be neglected in the planning process because it can have significant effects on a vast geographical area. The framework used in this study can help any planning agency to incorporate reliability in their planning process by using available local data.

This work can be improved in the future. The mode choice model can be substituted with any other type of choice models based on utility maximization. Results from different choice models can be compared to assess how the value of reliability differs in different choices. Another interesting comparison is comparing the model estimated with reported travel times versus the model with MWCOG travel times. Besides, the choice of reliability measure will affect the computed VOR and RR values (Carrion and Levinson 2012). Other reliability measures instead of standard deviation (for example, buffer index, planning time index, percent variation) can be used to analyze how it affects the results. One-hour intervals for reliability data can also be changed with smaller intervals to see the effect. The reliability forecasting part can be improved by adding weather or crash data to the regression. The mode choice model itself has many aspects that can be improved. Other modes such as bus may also be added in the future by collecting bus reliability data. By adding more modes, other types of discrete choice models such as mixed logit or nested logit should be tried to consider correlation between modes. Regarding incorporation with planning process, this study used value of reliability as a post processor to calculate reliability savings. One major future work is to incorporate reliability within planning models for enhanced sensitiveness. This requires a huge amount of reliability data for model estimation and calibration, but eventually it can improve the model’s behavioral response significantly.

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Table 1. Trips records in the 159 OD pairs in HHTS

Travel Mode	Rail	Driving	Other	Sum
Number of Trips	261	291	2	554
Percent	47.1%	52.5%	0.4%	100.0%

Table 2. Explanatory variables

Variable	Definition	Values
Veh	Number of household vehicles From HHTS	0 = 0; 1 = 1; 2 = 2; 3 = 3+
Lic	Have driver license?(Persons 16+) From HHTS	1 = YES; 2 = NO; -9 = Not Applicable
Age	Age in years From HHTS	Continuous (years)
Disc	Is the trip a discretionary trip or not (Trips with trip purpose other than home, work and school are considered discretionary trips) From HHTS	1 = YES; 2 = NO
TT	Travel time From HHTS	Continuous (min)
Cost	Travel cost From MWCOG	Continuous (cent)
TTR	Travel time reliability, which may be the 90^{th} minus 50^{th} percentile of travel time, standard deviation, and whole-day standard deviation From INRIX	Continuous (min)

Table 3. Model estimation results

Variable	No TTR		Standard Deviation	
	Coefficient	t-Stat	Coefficient	t-Stat
Constant (driving)	-1.830	-3.94	-1.660	-3.54
Veh	0.720	5.46	0.757	5.63
Age	0.217	3.14	0.203	2.90
Disc	0.941	4.35	0.869	3.98
TT	-0.005	-1.10	-0.007	-1.57
Cost	-0.001	-5.23	-0.001	-4.94
TTR	-	-	-0.122	-2.48
Summary Statistics				
Number of observations	521		521	
Likelihood Ratio Test	118.99		125.51	
Final log-likelihood	-301.64		-298.37	
Rho-square	0.165		0.174	
AIC	615.27		610.75	
Correlation between T and TTR	-		0.37	
P-value of the correlation	-		9.37	
VOR	-		56.31$/h	
95% CI of VOR	-		(54.14$/h, 58.51$/h)	
RR	-		4.02	

Table 4. Statewide AM peak hour savings for base and future years

Year	Total Savings	Travel Time Savings (Minutes)	Travel Time Savings ($)
Base Year	Travel Time	1,434,002	334,552
	Travel Time Reliability	144,255	180,191
Future Year	Travel Time	4,512,147	1,052,682
	Travel Time Reliability	454,639	569,313

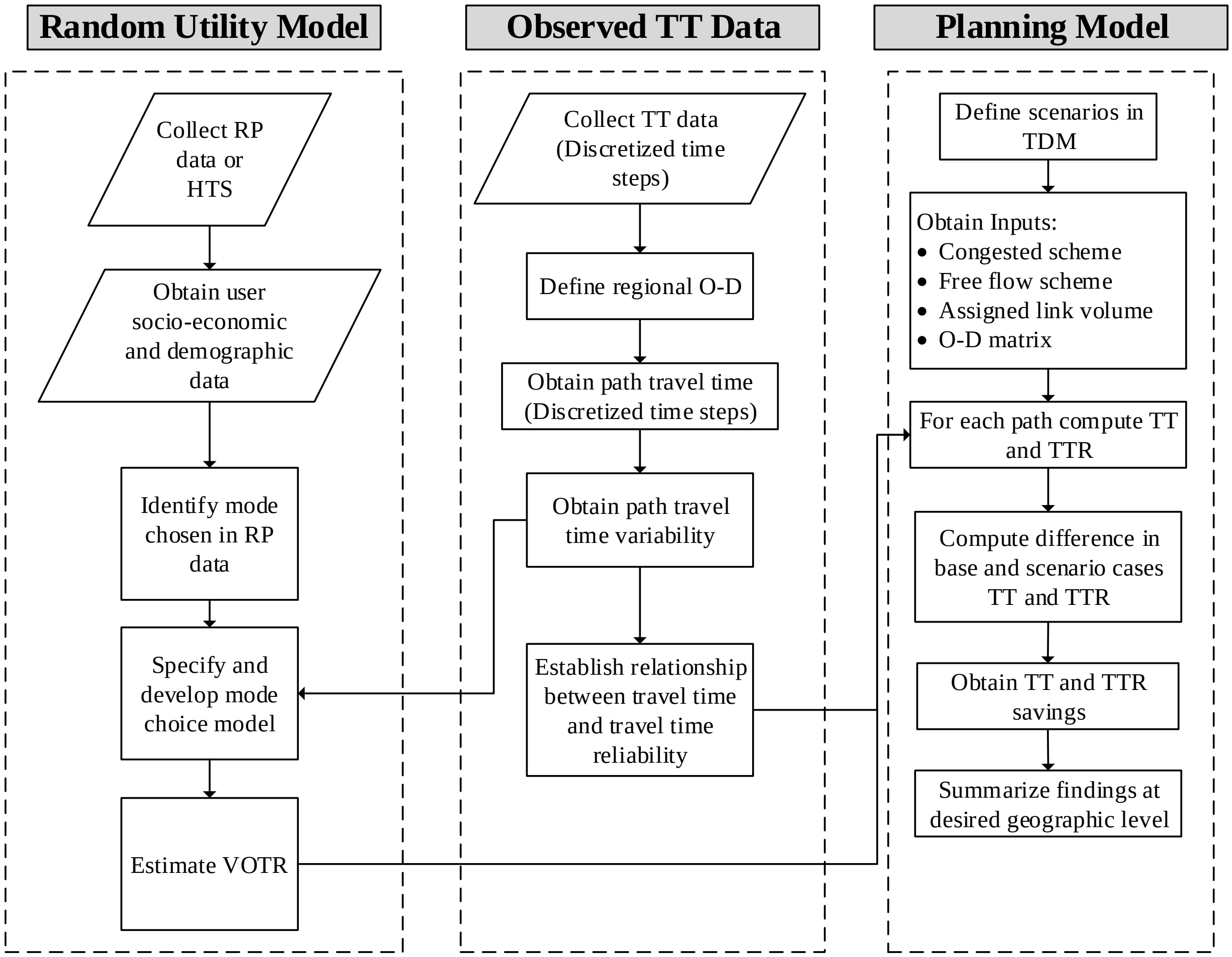


Fig. 1. Proposed methodology for VoTR estimation and integration in planning models

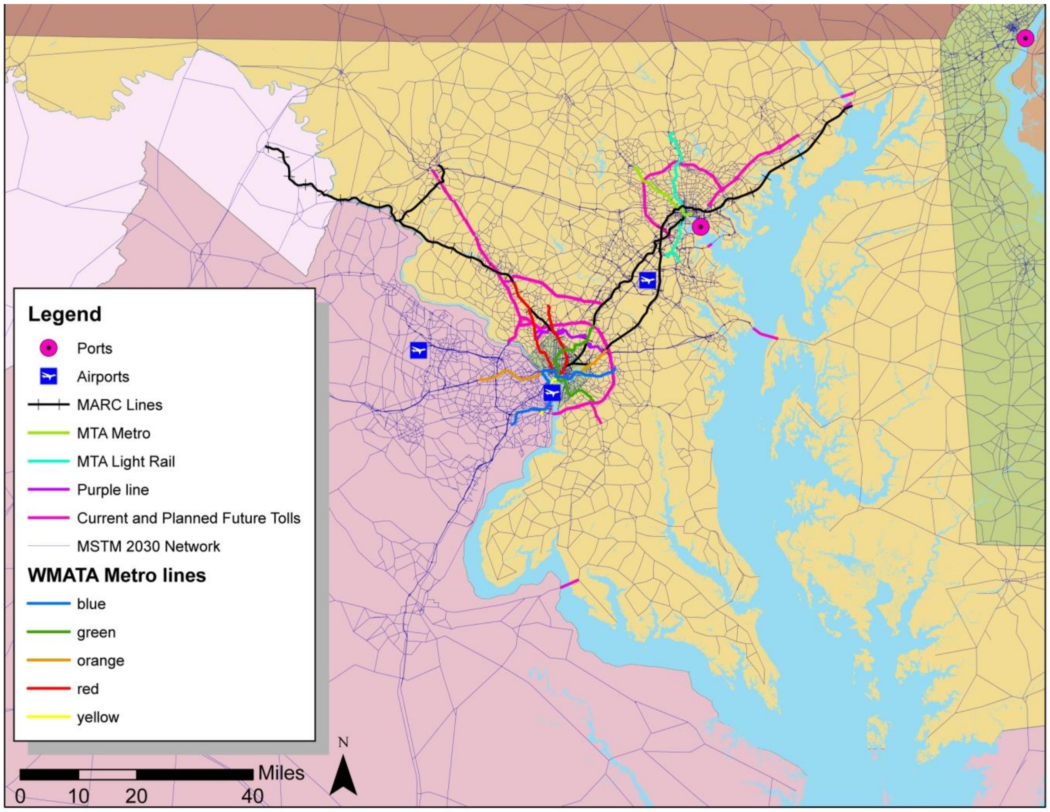


Fig. 2 (a). The state of Maryland highway and transit network.

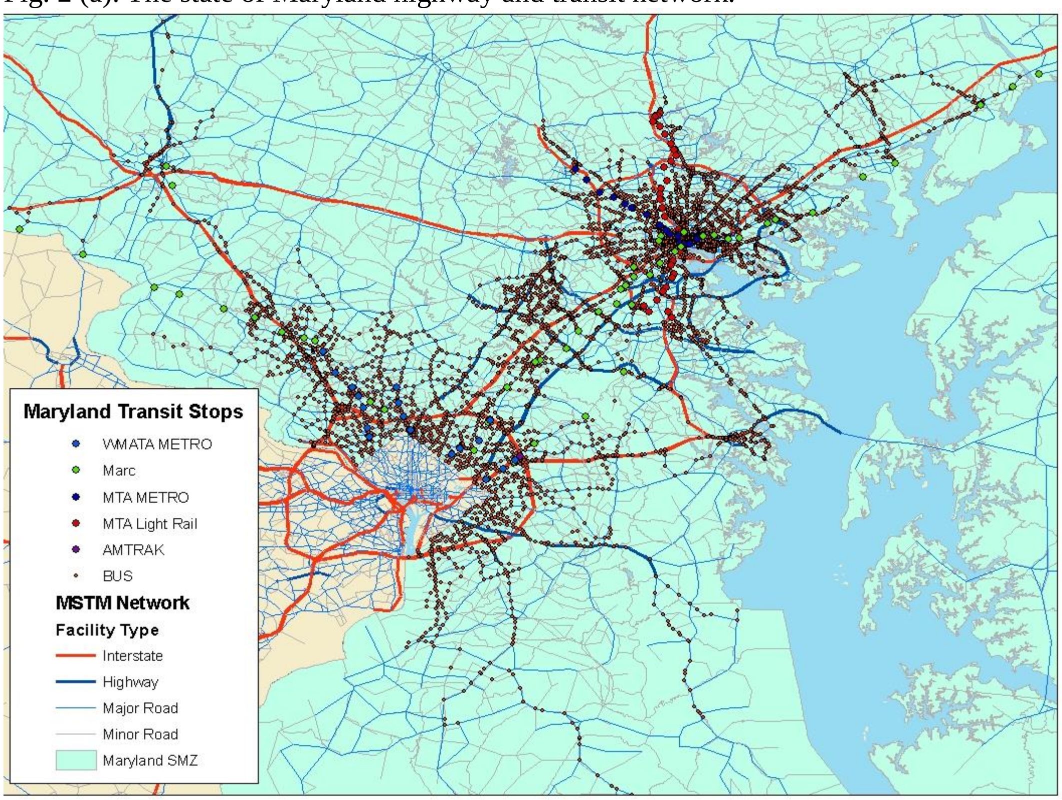


Fig. 2 (b). The state of Maryland transit stops.

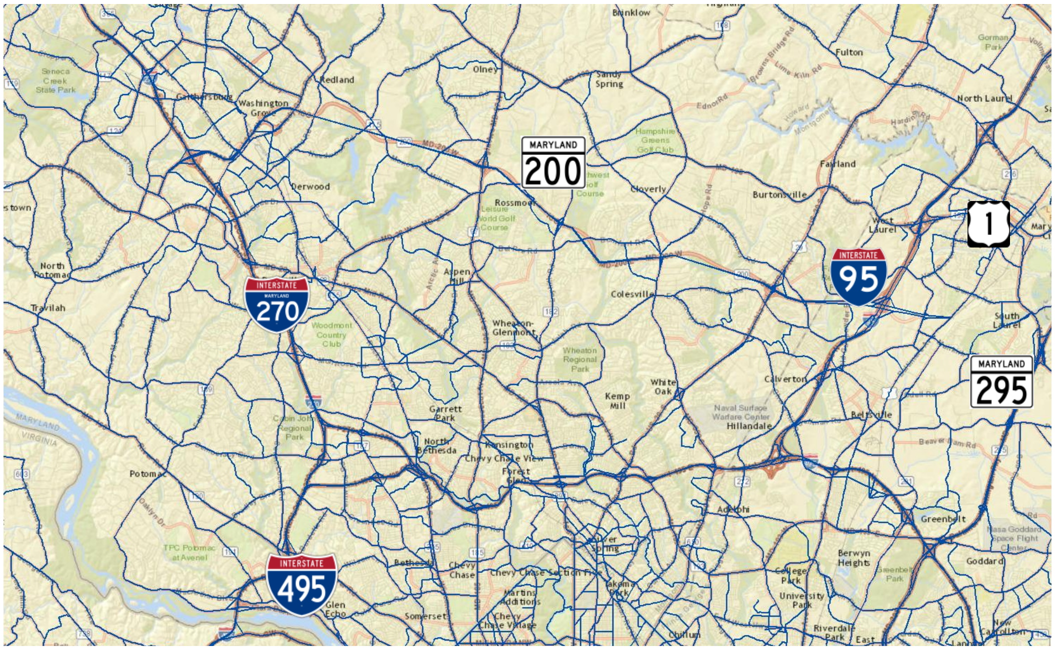


Fig. 2(c). ICC and other interstates in Maryland

Fig. 2. Maryland highway and transit network
(Note: WMATA-Washington Metropolitan Area Transit Authority, MTA-Maryland Transit Authority, SMZ-Statewide modeling zones MSTM-Maryland Statewide Transportation Model)

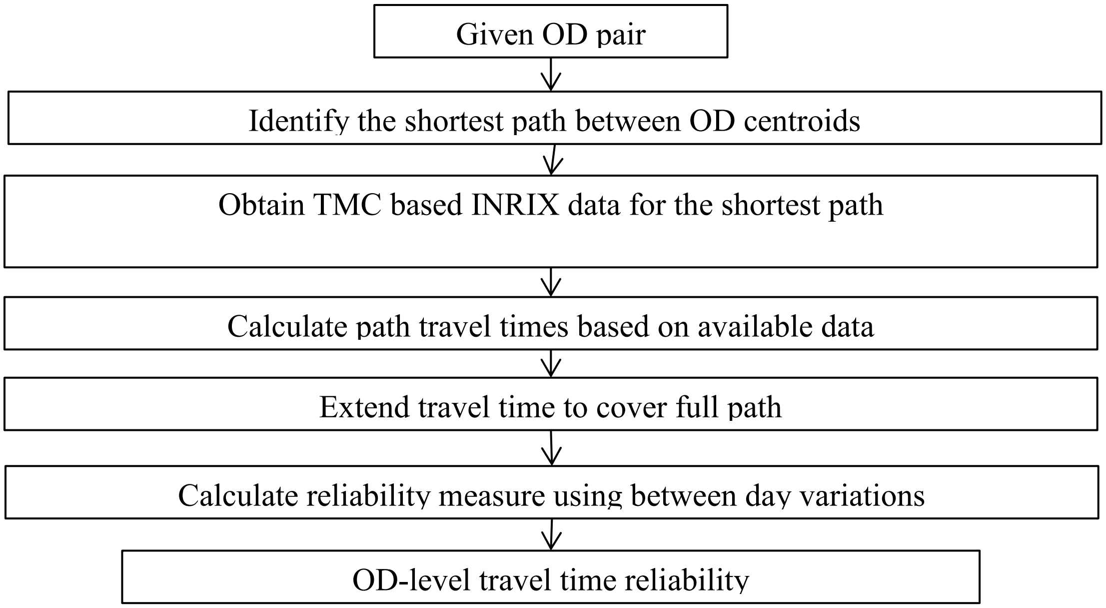
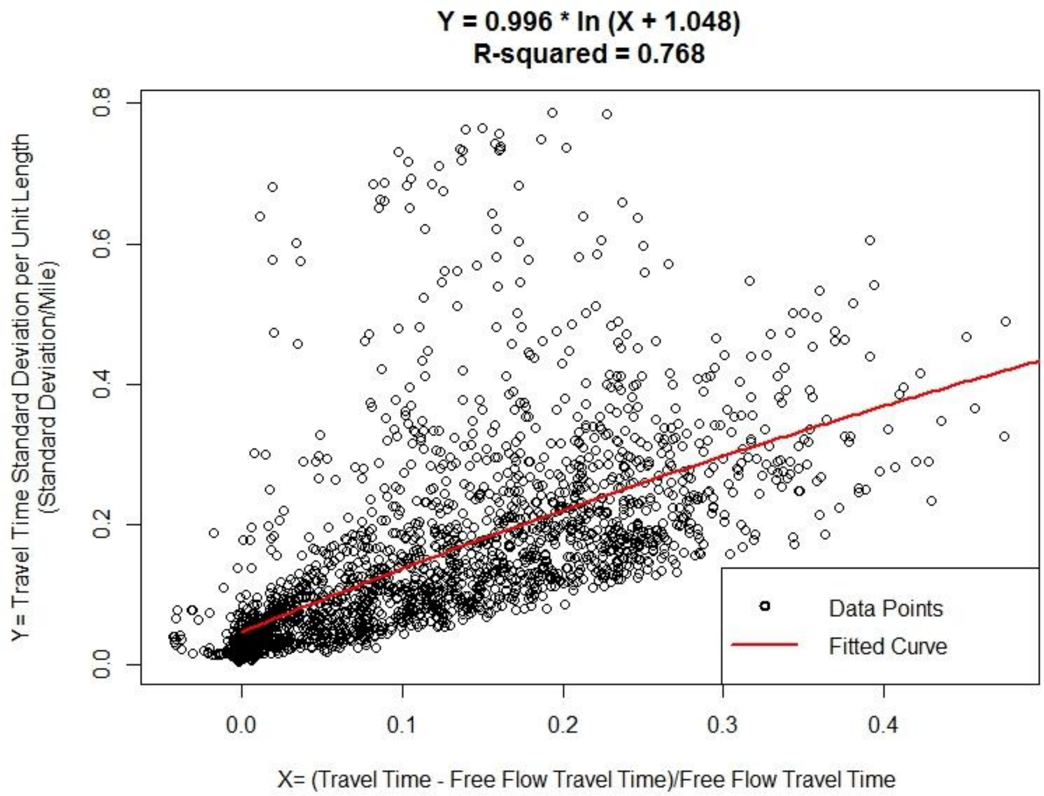
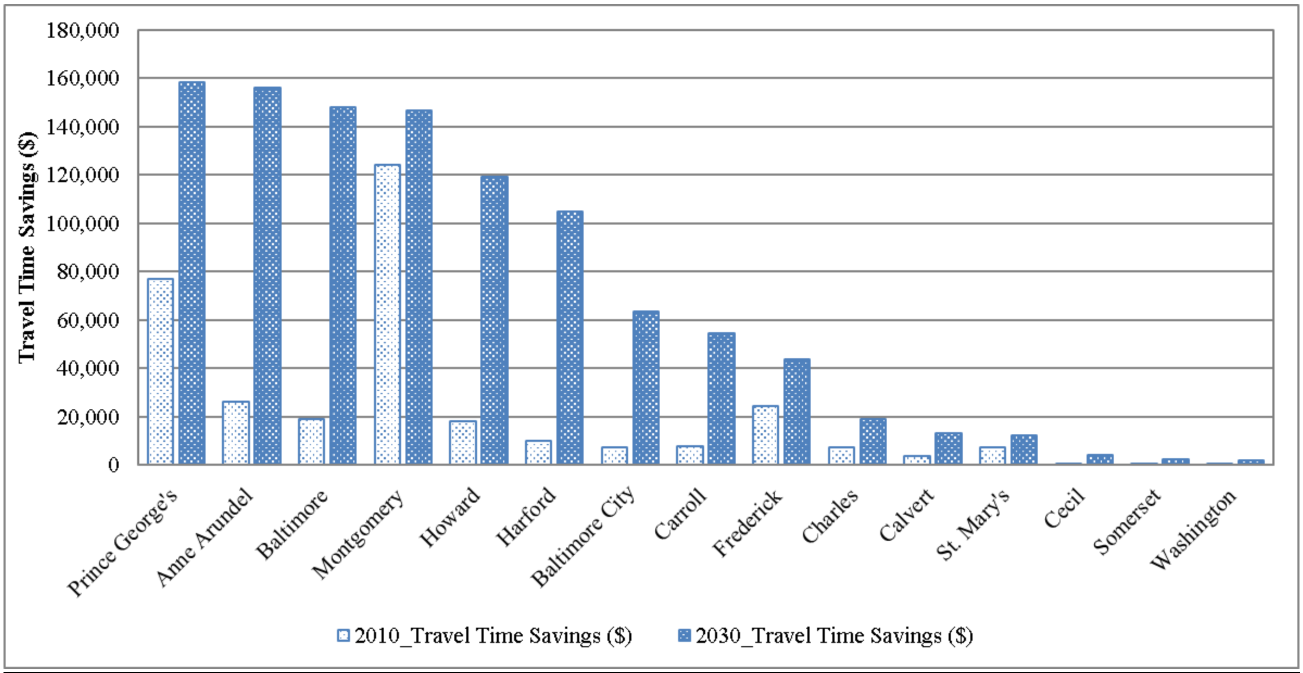


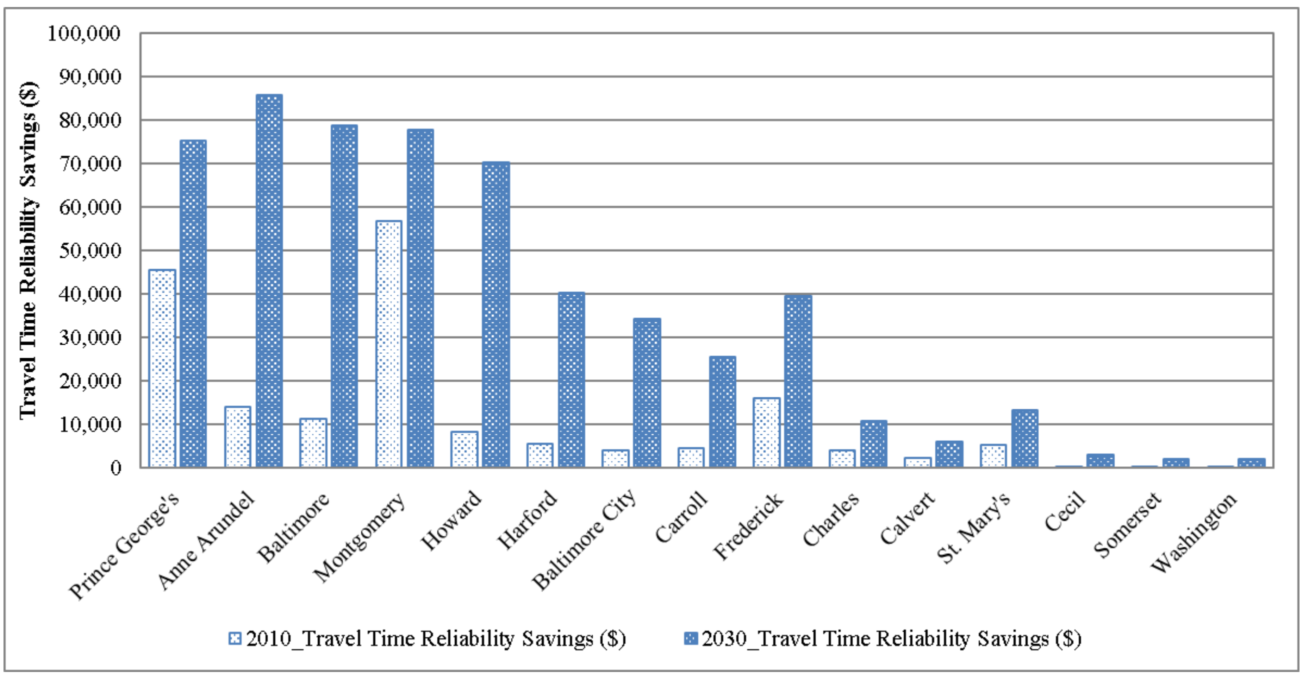
Fig. 3. Proposed OD level TTR estimation method



727 **Fig. 4.** Regression of standard deviation per mile with percent deviation from free flow time travel time



(a): County level travel time savings with base year build and future year build



(b) County level travel time reliability savings with base year build and future year build

Note: Counties not listed are: Wicomico, Worcester, Queen Anne's, Talbot, Dorchester, Caroline, Allegany, Kent, and Garrett

Fig. 5. County level travel time and travel time reliability savings

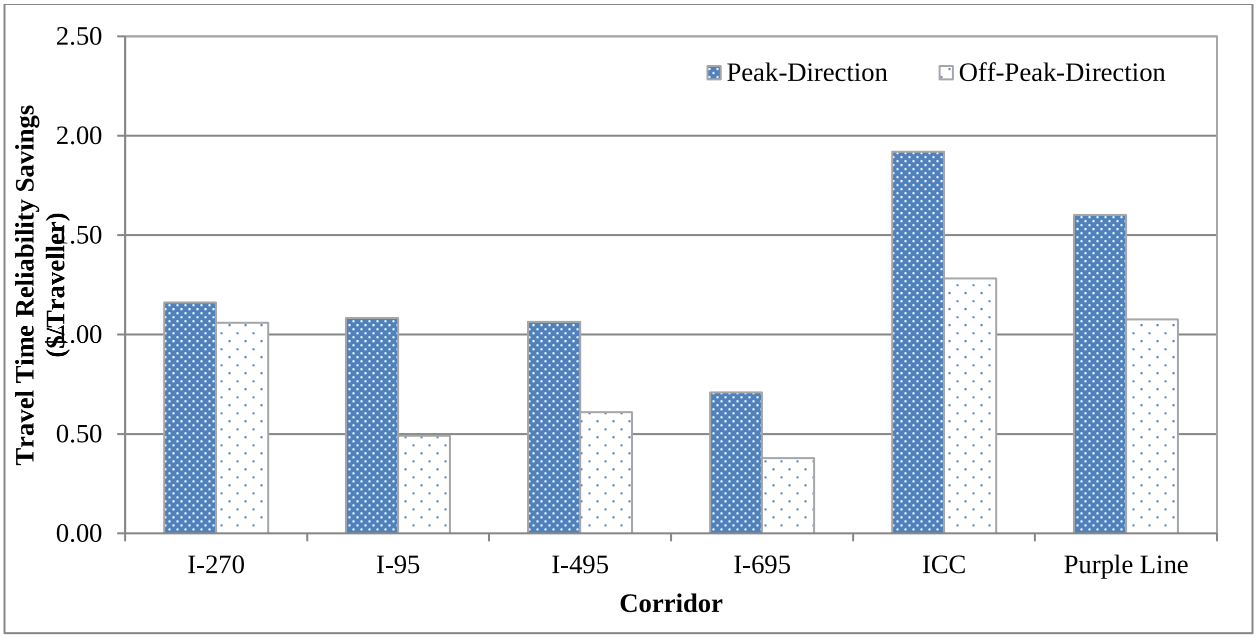


Fig. 6. Travel time reliability savings for sample interstate corridors the future year when compared to the no-build scenario (AM peak)