

# What do commuters think travel time reliability is worth? Calculating economic value of reducing the frequency and extent of unexpected delays

Nikhil Sikka · Paul Hanley

Published online: 8 December 2012  
© Springer Science+Business Media New York 2012

**Abstract** The measurement of transportation system reliability has become one of the central topics of travel demand studies. A growing literature concerns the measurement of value of travel time reliability which provides a monetary cost of avoiding unpredictable travel time. The goal of this study is to measure commuters' sensitivities to travel time reliability and their willingness to pay (WTP) to avoid unreliable routes. The preferences are elicited through a pivoted stated preference survey technique. To circumvent the issue of presenting numerical distributions and statistical terms to day-to-day commuters, we use the frequency of delay days as a means of measuring traveler's sensitivities to travel time reliability. The advantage of using simplified measures to elicit traveler preferences for travel time reliability is that these methods simply compare days with high delay to days with usual travel time. It was found that travelers are not only averse to the amount of unexpected delay but also to the frequency of days with unexpected delays. The paper presents WTP findings for three measures: travel time, frequency embedded travel time, and travel time reliability. The 'reliability' increase in WTP for travel time is found to be nearly proportional to the frequency of experiencing unexpected delays. For example, the WTP for mean travel time is calculated at \$6.98/h; however, reliability adds \$3.27 (about 50 % of \$6.98) to avoid unexpected delays '5 out of 10 days'. The results of the study would provide valuable inputs to cost-benefit analyses and traffic and revenue studies required for road tolling investment projects.

**Keywords** Route-choice · Frequency of unexpected delays · Mixed logit · Willingness-to-pay

---

N. Sikka (✉)  
Resource Systems Group, Inc., 180 Battery Street, Suite 350, Burlington, VT 05401, USA  
e-mail: nik.sikka@gmail.com

P. Hanley  
Department of Civil and Environmental Engineering, The Public Policy Center, University of Iowa,  
218 South Quadrangle, Iowa City, IA 52242, USA  
e-mail: paul-hanley@uiowa.edu

## Introduction

Commuters' sensitivities toward travel time reliability are an important component of travelers' route choice behavior. From a user's perspective, travel time can be divided into two parts: usual travel time (or mean travel time) and additional time. Usual travel time is the expected or predictable travel time which includes expected delays. Drivers take into account these expected variations in the travel time and undertake necessary actions like leaving home earlier to ensure on-time arrival to their destination. On the other hand, the additional time is related to any unexpected or random events such as inclement weather, unexpected traffic jams, or other disruptions. These random or unpredictable variations lead to unexpected delays and travelers may fail to exactly forecast their precise travel time to avoid late departures/arrivals. Travel time reliability is essentially a function of these unexpected delays rather than the usual travel time which includes predictable delays.

Travel time reliability has been conceptually associated with the travel time variability where travel time is characterized by a statistical distribution. Quantitatively, reliability is then assumed as a function of the spread of the travel time distribution. This makes sense from an analyst's point of view; however, surveys meant to elicit responses to variations in travel time reliability from respondents should avoid presenting alternatives in statistical and numerical terms. On the other hand, the Federal Highway Administration (Federal Highway Administration 2007) recommends using operationally based approaches to measure travel time reliability primarily because of their technical merit and the simplicity with which they can be used for system performance evaluation. Examples of these measures include *90th or 95th percentile travel time*, *buffer index*, *planning time index*, and *frequency that congestion exceeds some expected threshold* (see the next section). These measures, if presented in a simplistic way, can be more useful in eliciting traveler preferences toward travel time reliability and therefore, more realistic willingness-to-pay (WTP) measures can be calculated.

The goal of this study is to understand commuters' route choice behavior in the presence of travel time unreliability and to calculate their willingness to pay metrics to avoid unreliable routes. This paper improves upon existing methodologies by deploying stated preference (SP) survey techniques that utilize a frequency of unexpected delay day's methodology to characterize travel time reliability, rather than more technical distributions of time which are often a source of confusion among survey respondents. In doing so, this research aims to contribute a simpler and more realistic method of measuring travelers' WTP in the presence of trip reliability issue.

## Literature review

### Measurement of travel time reliability

A lack of a clear definition or agreed upon system of measurement adds considerably to the murkiness of placing a value on travel time reliability. Lomax et al. (2003) treat reliability in terms of consistency of transportation services for a given time period while Emam and Al-Deek (2006) define travel time reliability as the probability of completing a trip within a specified range of time. van Lint and van Zuylen (2005) provide a more detailed description of travel time reliability by defining it as the consistency in travel times based on the time of day, day of the week, month of year, and other external factors. In order to effectively communicate network reliability to travelers and practitioners, the Federal

Highway Administration (2007) sets out some of the clearest guidelines to study reliability and recommends using the following measures/indicators:

- *Percentile travel times*: An estimate of travel time reliability in terms of traffic delays on a particular route on worst traffic days (presented in minutes). Based on the study requirements, this metric can be presented as 95th percentile travel times, but 85th, 90th or 99th percentile travel times can also be calculated.
- *Buffer index*: The extra travel time (in minutes) travelers should provide a cushion for in order for them to finish a trip on-time. It can also be presented as a percentage given by the normalized difference between the 95th percentile time and the mean travel time.
- *Planning time index*: The near-worst case travel time that takes into account both the typical traffic delay and any unexpected delays.
- *Frequency that congestion exceeds some expected threshold*: The percent of days or occurrences that average travel time exceeds a certain pre-defined value.

These measures basically provide an indication of day-to-day consistency in travel times in the presence of any unexpected delays. For example, a particular route may have a usual travel time of 15 min; however, in the event of non-recurrent congestion, the same route may take 25 min for a particular trip. The measures listed above capture travel time reliability in a way that can be easily understood by the non-technical highway travelers. There is a growing literature on how to calculate these measures from traffic engineering standpoint and several studies have come up with reliability metrics that may be used for system performance and evaluation studies (Chen et al. 2003; Lyman and Bertini 2008). However, missing in these studies is the economic valuation of reliability from travelers' perspective. How do commuters make route choice decisions and put a monetary value to travel time on a particular route when reliability is presented in a manner similar to discussed above? This study aims to fill this gap using a SP survey methodology.

### Value of travel time reliability

Willingness to pay or value of travel time (VOT) has been extensively studied in many transportation contexts (Small and Verhoef 2007; Wardman 2004). Studies related to WTP for travel time reliability, on the other hand, are only recently gaining attention. Nevertheless, a systematic inclusion of these measures in transportation project evaluation and decision-making is still absent. A recent synthesis of research on the value of time and reliability, prepared by the Center of Urban Transportation Research (Center for Urban Transportation Research 2009), contains a detailed review on previous studies on value of reliability.

The utility maximization approach has been the most widely framework to account for travel time variability. Earlier works capturing travel time reliability involved the use of a mean–variance approach as proposed by Markowitz (1952). Expected utility (EU) theory has also been widely used to calculate VOT and value of reliability (VOR) measures and to capture travel time uncertainty in route choice context (Bates et al. 2001; Li et al. 2010; Noland and Small 1995; Noland et al. 1998; Small et al. 1999). The concept of reliability ratio (defined as the marginal rate of substitution between travel time and travel time reliability) was also put forward to inter-relate the VOT and VOR measures. Table 1 summarizes recent studies using this measure.

Most of the studies based on EU theory used SP methodology to measure travelers' sensitivities toward travel time reliability. The presentation of reliability in these studies

**Table 1** Summary of previous studies

Study	Survey technique	Modeling framework	Reliability/variability presentation	Reliability measures	Mean reliability ratio
Abdel-Aty et al. (1997)	SP	Discrete choice logit models	Choice between a route with fixed travel time, and a route with 20 min 4 days/week and 40 min 1 day/week (values changed for different alternatives)	Standard deviation around mean travel time	N.A.
Noland et al. (1998)	SP	Discrete choice logit models	Five different travel times for each alternative	Standard deviation; coefficient of variation (standard deviation divided by mean travel time); scheduling delay	1.27
Small et al. (1999)	SP	Discrete choice logit models	Five arrival scenarios (late, on time and early) for each alternative with equal probabilities	Standard deviation; scheduling	3.22
Bates et al. (2001)	SP	Mean–variance (linear programming)	10 arrival possibilities (late, on time and early) for each alternative	Scheduling	N.A.
Small et al. (2005)	RP and SP	Discrete choice logit models	Different frequency of unexpected delays of 10 min or more for each alternative	Difference between the 80th and 50th percentiles of the distribution of travel time	1.87
Tilahun and Levinson (2010)	SP	Discrete choice random parameter binomial logit model	Distribution of travel time	Three measures based on travel time distribution: cumulative probability of arriving late or early, aggregate lateness probability, and standard deviation	0.89
Li et al. (2010)	SP	Discrete choice logit models	Probabilities of three arrival times (late, on time and early) for each alternative	Standard deviation around mean travel time	0.08–1.43
Carrion and Levinson (2011)	RP based on GPS data	Discrete choice logit models	Actual commute experience revealed preference (ACERP)	Three measures based on travel time distribution: cumulative probability of arriving late or early, aggregate lateness probability, and standard deviation	0.20–1.20

(see Li et al. 2010 for a review) either involved various possible travel times for hypothetical routes or route alternatives with equal probabilities of various arrival time possibilities (late, on time, or early). The approach measures travelers' preferences for being early or late rather than the reliability of the route itself. In reality, travelers do not have such detailed information about the possible arrival time distributions. Moreover, a driver's decision making is influenced by prior experience and it is more likely they remember the frequency of some bad days with higher than usual travel times, instead of the overall travel time distribution.

Abdel-Aty et al. (1997) also analyzed commuters' attitudes toward travel time reliability and traffic information using two SP survey techniques—a computer aided telephone interview, and a mail back survey. This study also used the concept of frequency of delay by presenting two hypothetical route options: one with a fixed travel time and the other with two different travel times/week. The fixed travel time route always had a longer travel time, and the other route was always shorter but with uncertain reliability. Despite having some attractive properties, there are limitations with this survey approach. First, the SP questions did not include a cost attribute prohibiting the calculation of WTP measures. Second, since one of the routes always had a fixed travel time the survey was subjected to 'certainty effect' (Tversky and Kahneman 1986) implying that decision makers tend to select an alternative with certainty over the other alternative, despite the more certain alternative having no clear advantages. Finally, frequency of delay was not included in the calculation of reliability measures; instead the study calculated the SD of travel time as a measure of reliability.

Small et al. (2005) arrived at VOR estimates using both the revealed preference (RP) and SP data from morning commuters on California State Route 91 (CA-91). Travel time reliability was presented as the frequency of an unexpected delay of 10 min or more making this the only comparable study using a similar survey methodology to the one being proposed here. However, important differences should be pointed out. The unexpected delay time in Small et al. (2005) was essentially assumed to be distributed and the decision makers were allowed to be motivated by extreme values of the right range. Also, the formulation for the unreliability of travel time was based on the difference between the 80th and 50th percentiles of resulting travel time distributions.

Carrion and Levinson (2011) used global positioning system (GPS) devices to collect RP travel data of travelers on high occupancy toll (HOT) lanes on I-394 in Twin Cities to obtain VOR measures. While innovative and successful, the study acknowledged the high cost of conducting such surveys as a limitation for this methodology.

It is challenging to elicit accurate responses from day-to-day commuters if travel time reliability is presented using statistical probabilities and distributions. The contribution of this study is our effort to express travel time reliability based on two-dimensions; the frequency of unexpected delay, and the magnitude of unexpected delay. It is not implied that previous studies have failed to calculate correct VOR measures. Instead, this study's contribution is using terms that are more readily understood by commuters so that more realistic WTP measures for travel time and reliability can be obtained. To our knowledge, no previous study has calculated travel time reliability as a function of both the frequency of days with unexpected delays and the amount of unexpected delay.

## Model formulation and theoretical approach

The hypothesis of this study is that commuters do not make route choice decisions based on just mean (or usual) travel time and travel cost, but also on the extent of unexpected

delays due to nonrecurring events. Furthermore, it is not only the amount of unexpected delay that should be taken into account but the frequency of experiencing unexpected delays should also be included, when measuring drivers’ choices. Presenting frequency and amount of unexpected delays instead of travel time distributions limits the confusion among the respondents.

The related hypothesis is that if commuters’ route choice preferences are influenced by travel time reliability, then it is possible to unravel the economic value of time and the economic VOT reliability. The two concepts can also be seen as inter-connected since reliability is essentially represented in terms of time. Therefore, it is possible to have a combined measure of travel time savings and travel time reliability. Improvement in reliability can be realized with or without improvement in travel time, and by doing so, traditional revenue forecasts and usage may increase by investing in congestion reduction schemes.

To test the hypotheses, a SP survey technique was used to determine the effect of various factors and attributes on the observed outcomes and through inference respondents’ WTP for attributes of interest was calculated. Hensher et al. (2005); Bliemer and Rose (2010), and (2011) provide a good overview of SP surveys as applied in transportation studies.

A random utility choice modeling framework and in particular, a logit model is a common analytical approach for analyzing people’s choice behavior in the case of repeated observation. The multinomial logit model calculates a choice probability for each alternative presented in the SP questions. A simple utility equation (in scalar form) for each alternative in the SP tradeoff exercises can be written as:

$$U_1 = \beta_1x_1 + \beta_2x_2 + \beta_3x_3 + \dots + \beta_nx_n + \epsilon_n \tag{1}$$

Here, each  $x$  represents a variable included in the SP design (route attributes and their interaction with the traveler’s characteristics) and the corresponding  $\beta_n$  are the estimated model coefficients. The multinomial logit model calculates systematic taste variation in the sample data and produces only a single value for each coefficient in the model. However, ignoring heterogeneity among responses from different individuals, also known as random taste variation, can lead to inconsistent estimates of the effects of study variables on choice outcomes (Hsiao 1986). Mixed logit specification is one of the most flexible approaches to estimate heterogeneity in taste variation and can approximate any random utility model (McFadden and Train 2000). Using a mixed model specification, coefficients such as travel time and cost can be specified as random parameters and modeled as distributions rather than fixed values. The mixed logit model produces two coefficient estimates for each random parameter—a mean ( $\beta'$ ) and a SD ( $\sigma_q$ )—that define the shape of the randomly distributed parameter. The utility in vector form can now be written as:

$$U_{nsi} = \beta_nx_{nsi} + \epsilon_{nsi} \tag{2}$$

Here, the index  $n$  ( $n = 1, 2, \dots, N$ ) is used for the respondents,  $s$  for the choice set, i.e. SP choice scenarios for a particular respondent, ( $s = 1, 2, \dots, S$ ). and  $i$  for the route alternative ( $i = 1, 2, \dots, I$ ). For mixed logit specification,  $\beta_n$  can be specified as:

$$\beta_n = \beta' + v'_n \tag{3}$$

Here,  $\beta'$  is the  $(Q \times 1)$  is the vector of the mean effects of the observed variables  $x_{nsi}$  and  $v'_n$  is another  $(Q \times 1)$  randomly distributed vector which captures unobservable heterogeneity among individuals (with mean zero and variance,  $\sigma_q^2$ ). In order to retrieve the

parameters  $\beta$  and  $\sigma_q$  we calculate a log-likelihood function for all respondents, which is given as:

$$L(\beta, \sigma) = \sum_{i=1}^n \log \int_{v_n} L_n(\beta|v_n) f(v_n|\sigma) dv_n \tag{4}$$

where

$$L_n(\beta|v_n) = \prod_{s=1}^S \left[ \prod_{i=1}^I \frac{\exp(\beta' x_{nsi} + v_n x_{nsi})^{y_{nsi}}}{\sum_{j=1}^I \exp(\beta' x_{nsi} + v_n x_{nsi})} \right] \tag{5}$$

The above integral does not have a closed form, and is approximated via simulation to retrieve the mean and the SD of each explanatory variable (Train 2009).

**Data collection**

The SP survey instrument was administered online. Invitees included University of Iowa Alumni living in the Chicago-Naperville-Joliet Metropolitan Division area (Illinois), Dallas-Fort-worth-Arlington Metropolitan area (Texas), Harris County (Texas), Miami Dade County (Florida), New York, and New Jersey. These regions were well suited for the study because of the presence of well-established tolled highway routes characterized by heavy use and traffic congestion with itinerant and unexpected delays. Invitations and follow-up e-mails were sent by the University of Iowa alumni office to about 8,100 members. A total of 292 alumni members completed the online survey yielding a response rate of approximately four percent.

**Survey design**

Based on the study objectives, four route-attributes were included in the SP surveys to describe the choice alternatives:

1. *Usual travel time*: Typical travel time (in minutes) from home to work given there is no unexpected delay.
2. *Frequency/chance of unexpected delay*: Presented as the number of days a driver can experience unexpected delays out of 10 days (10 days means 2 weeks assuming 5 working days in a week). As such, ‘5 days out of 10 days’ means that a commuter is likely to experience unexpected delays on a route 5 times out of 10 times on that route. This method avoids statistical nomenclature and is relatable for most commuters.
3. *Average delay*: Mean delay (in minutes) on the days travelers experience any unexpected delays.
4. *Toll cost*: One-way toll for the route.

The survey was divided into three sections. The first contained questions related to respondents’ existing travel characteristics, the second had a series of choice scenarios, and the final section asked about socio-demographic characteristics.

In the choice scenario section, the first question asked respondents to make a choice between their existing route and two hypothetical routes. In the second question,

The screenshot shows a web-survey interface with a progress bar at the top. Below it is a table of route characteristics comparing 'Your recent trip' with two hypothetical routes, 'Route One' and 'Route two'. The table includes attributes like travel time, chances of delay, average delay, and toll cost. Below the table are two choice questions with radio buttons for each option. At the bottom, there are 'Back' and 'Forward' navigation arrows.

Route Characteristics	Your recent trip	Route One	Route two
Usual travel time	25 minutes	18 minutes	12 minutes
Chances of unexpected delay	2-3 times in 10 days	5 out of 10 days	1 out of 10 days
Average delay time	15 minutes	12 minutes	12 minutes
Toll cost	\$0.00	\$1.00	\$2.00

If you make the same trip again, which road would you choose?

Your existing route is undergoing long-term construction and is not a viable option any more. If you could only choose between Route 1 and Route 2 now, which route would you choose?

Back Forward

**Fig. 1** Screenshot of the web-survey

respondents were asked to assume that the existing route was no longer available, and they were to make a choice between two hypothetical routes only (see Fig. 1). The aim of the study is to understand commuters' route choice behavior toward different levels of travel time reliability. Therefore only responses when respondents were forced to make a choice between two hypothetical routes are analyzed in this paper.

The SP experiments used a pivoted choice experiment methodology where the levels of the route attributes were presented as somewhat above and below respondents' reported trip characteristics (as shown in Table 2). Attributes were varied in the choice tasks using a blocked fractional-factorial experimental design ensuring that no choice sets had a dominant alternative (i.e. one attribute's level was either so high or so low creating situations where respondents did not make a tradeoff). In all, 12 choice questions were presented to each respondent. In this study, only eight of the 12 choice questions were analyzed where the frequency of unexpected delays was known (i.e. the levels vary from '1 out of 10 days' to '9 out of 10 days'). Figure 1 represents a screenshot of one of the choice questions. More detailed discussion on survey design can be found in Sikka (2012).

It is worth mentioning some caveats related to external validity of SP surveys arising due to representativeness of the sample and hypothetical bias in the survey responses. From the viewpoint of representativeness, the external validity of our survey results may be limited, since the sample was drawn from the University of Iowa's alumni members. The sample mostly included employed, higher than median income, college graduates, and people living in major urban metropolitan areas. Therefore, due care should be given before generalizing the results to the population as a whole. The other usual issue related to the external validity of SP surveys is due to the hypothetical bias in the survey responses. In other words, how likely it is that the preferences elicited in SP surveys actually match respondents' 'real-life' behavior? This problem can be overcome by either comparing SP data with revealed preference (RP) data, or by maximizing realism in the hypothetical SP scenarios, or both. Due to the nature of this study and the way the reliability is presented in the choice scenarios, RP data was not easy to collect. However, the realism in the survey was maintained by asking details of respondents' existing commute trips and pivoting the SP hypothetical choice scenarios around that. Having acknowledged this, choice models



**Table 2** Attributes and levels in the survey design

Levels	Usual travel time (%)	Frequency of unexpected delay	Average delay if occurs (%)	Toll cost
Level 1	–50	1 out of 10 days	–50	–100 %
Level 2	–25	3 out of 10 days	–20	–50 %
Level 3	–10	5 out of 10 days	+50	+ \$1
Level 4	+50	7 out of 10 days	+20	+ \$2
Level 5	+25	9 out of 10 days		+ \$3
Level 6	+10	Unknown		

**Table 3** Summary of socio-economic and trip characteristics

Sex (male, female)	(54.1 %, 45.9 %)
Age (mean, SD)	(39.75, 11.29)
Personal income	
Up to \$40,000	9.7 %
\$40,001–\$60,000	17.5 %
\$60,001–\$90,000	23.0 %
\$90,001–\$120,000	17.5 %
Greater than \$120,000	32.3 %
Usual travel time in min (mean, SD)	(29.90, 14.80)
Unexpected delay in Min (mean, SD)	(13.71, 10.82)
Toll in \$ (mean, SD)	(0.45, 0.97)

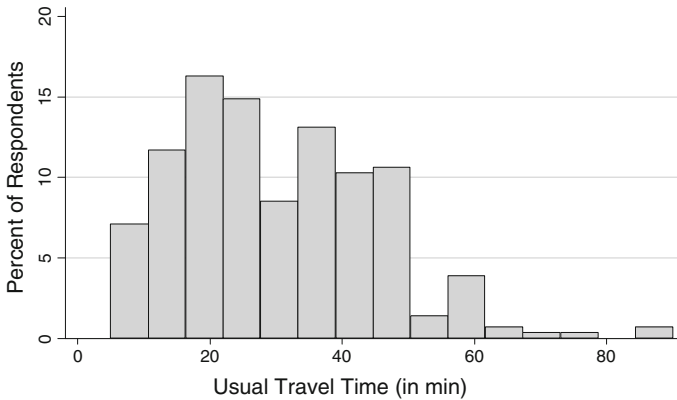
based on SP data in route choice analysis are normally representative. For example, a recent before-and-after study done by Devarasetty et al. (2012) showed that maximum WTP for travel on managed lanes did not change much before and after the SP surveys were conducted on Houston Katy Freeway managed lanes.

## Results

### Descriptive analysis

A total of 292 automobile commuters completed the survey online. The number of responses was reduced to 273 after excluding the respondents with commuting times less than 5 min. Table 3 provides a summary of the socio-demographic characteristics of the respondents (who chose to provide that information) along with their reported trip characteristics.

The dataset includes a wide range of ages, with a mean age of about 40 years. About 54 % of survey takers were male. The sample has a higher percentage of medium to higher income groups with about 50 % of respondents having household income greater than \$90,000. The average commute time across the sample was calculated as 29.9 min (Fig. 2 shows the distribution of usual travel time in the sample). The average unexpected delay on days when respondents experienced unexpected delays on their commuting routes was observed to be 13.7 min. In terms of the frequency of experiencing unexpected delays, about two-third of the respondents experience unexpected delays at least 4–5 times in



**Fig. 2** Distribution of usual travel times of survey respondents

2 weeks time. Lastly, about one-third of the respondents pay tolls for their commuting routes. The average toll across commuters who pay tolls came out to be \$1.45 (SD \$1.26), whereas, the average toll across all the respondents was calculated as \$0.45 (SD \$0.97).

### Empirical analysis

The statistical analyses and mixed logit model estimation were conducted using the SP choice data. In order to test the study hypotheses, several mixed logit utility specifications were tested using the four route attributes discussed earlier, as well as trip characteristics, and demographic variables. Several utility equations were specified and tested in order to determine whether drivers' sensitivities toward travel time reliability, toll cost, and travel time are dependent on their trip and demographic characteristics. The random parameters in the mixed logit specification are assumed to be normally distributed. The estimation was done using BIOGEME software (Bierlaire 2008). For simulation purposes, 500 pseudo random draws were used for randomly distributed parameters. Results of the final estimation are shown in Table 4.

As expected, negative and statistically significant coefficient estimates are observed for usual travel time, average unexpected delay time, and toll cost attributes, indicating negative relationships between the overall utility and these variables. The effect of travel time reliability on commuters' choice is calculated by including two variables; first, the variable frequency/chances of unexpected delay attribute is included as a separate categorical variable (main effects) and the second variable is calculated by interacting each of its level with the amount of unexpected delay. The category '1 day out of 10 days' formed the base category for the model estimation. As a comparison, the coefficient estimate of  $-0.741$  for the category '5 days out of 10 days' in Table 4 implies that, on average, a route that is likely to have unexpected delays '5 days out of 10 days' is 0.741 utility units less attractive than a route that is likely to have unexpected delays '1 day out of 10 days' for a given delay time. Moreover, a significant interaction term between this category and the amount of unexpected delay shows that a route that is likely to have unexpected delays '5 days out of 10 days' is preferred even less by 0.028 units as the amount of delay increases. Similar results are obtained for other categories (including '7 days out of 10 days' and '9 days out of 10 days') and when interacted with delay variable. The main effects for the category '3 days out of 10 days' are found to be insignificant when compared with the base category, however, a significant interaction

**Table 4** Mixed logit model results

Attributes	Coefficient	lr values
Usual travel time	−0.083	4.42
SD usual travel time	0.082	2.55
Average delay time	−0.046	2.43
Frequency of delay		
1 day out of 10 days	Ref.	–
3 days out of 10 days	0.098	0.66
SD 3 day out of 10 days	0.002	0.12
5 days out of 10 days	−0.741	3.70
SD 5 day out of 10 days	0.623	2.07
7 days out of 10 days	−0.749	3.75
SD 7 day out of 10 days	0.275	0.77
9 days out of 10 days	−0.496	1.93
Toll	−0.738	8.16
Interactions		
1 day out of 10 days × Delay	Ref.	–
3 days out of 10 days × Delay	−0.021	2.01
5 days out of 10 days × Delay	−0.028	2.41
7 days out of 10 days × Delay	−0.056	3.61
9 days out of 10 days × Delay	−0.079	4.17
Toll × dummy for low to medium income (<\$60 K)	−0.002	1.89
Toll × dummy for who already pay tolls	0.201	2.04
Final log-likelihood	−1226.15	
Likelihood ratio test	442.28	
Adjusted $\rho^2$	0.141	
Number of choices	2,088	
Number of individuals	273	

term with the delay variable implies that respondents' route choice preferences do not differ between the base category and the category '3 days out of 10 days' unless a route with the chances of experiencing unexpected delays '3 days out of 10 days' has a higher delay time. A significant SD (or unobserved heterogeneity) corresponding to the '5 days out of 10 days' category was found. However, the model results did not show any unobserved heterogeneity in the categories '3 days out of 10 days', '7 days out of 10 days', and '9 days out of 10 days'.

Importantly, Table 4 also shows that respondents prefer routes that are more reliable with less unpredictable delays. The significance of interactions between various levels of frequency of unexpected delay days and the amount of unexpected delay highlight a very useful result and confirms our first hypothesis that commuters prefer a route that not only has less amount of unexpected delay but also more consistent over a period of time.

To account for any systematic heterogeneity, interactions between route and demographic characteristics were tested and found to have no significant interactions with the exception of weather a respondent indicated to have paid a toll on a recent trip. In Table 4, corresponding to the toll dummy, a positive coefficient of 0.201 implies that commuters who already pay tolls for their existing route have a tendency to pay higher tolls to save time than commuters who do not pay tolls.

WTP estimates

One of the study hypotheses was that if commuters’ route choice preferences are influenced by travel time reliability, then it is possible to unravel the economic value of time and the economic VOT reliability. The marginal rate of substitution of various attributes and toll cost coefficients can be used to calculate implied WTP values. Three different WTP measures are calculated in this study: the WTP for travel time, the WTP for frequency embedded travel time, and the WTP for travel time reliability.

In this study, a fixed parameter for the toll cost coefficient was assumed and the coefficients of interests for which the WTP measures needed to be calculated were allowed to vary randomly. By fixing the cost coefficient, many undesirable properties of the resulting WTP distribution can be avoided. For a detailed review of various empirical approaches to calculate WTP measures, please refer to Daly et al. (2011). Based on the modeling results, the utility function can be written as:

$$U_{nsi} = (\beta_1 + v_1) \text{Usual Travel Time} + \beta_2 \text{Average Delay Time} + (\beta_{3i} + v_2) \text{Frequency Delay} + \beta_{4i} \text{Frequency Delay} * \text{Average Delay Time} + \beta_5 \text{Toll} + \beta_6 \text{Toll} * \text{Existing Toll} + \varepsilon_{nsi}$$

where  $v_1$  and  $v_2$  are the normally distributed random terms that allow for the random taste variation among respondents for the usual travel time and frequency of unexpected delay parameters. The marginal utilities are given by the partial derivatives of the utility function (Eqs. 6 through 9) with respect to usual travel time ( $T$ ), frequency embedded travel time ( $FT$ ), cost ( $C$ ) and reliability ( $R$ ).

$$\frac{\partial U}{\partial T} = \beta_1 + v_1 \tag{6}$$

$$\frac{\partial U}{\partial FT} = (\beta_1 + v_1) + \beta_2 + \beta_{4i} \text{ Frequency Delay} \tag{7}$$

$$\frac{\partial U}{\partial C} = \beta_5 + \beta_6 \text{ Existing Toll} \tag{8}$$

$$\frac{\partial U}{\partial R} = (\beta_{3i} + v_2) + \beta_{4i} \text{ Average Delay Time} \tag{9}$$

Three measures namely, the WTP for travel time, the WTP for frequency embedded travel time, and the WTP for travel time reliability can now be calculated using Eqs. (10 through 12):

$$w_t = \frac{\partial U}{\partial T} / \frac{\partial U}{\partial C} = \frac{\beta_1 + v_1}{\beta_5 + \beta_6 \text{ Existing Toll}} \tag{10}$$

$$w_{ft} = \frac{\partial U}{\partial FT} / \frac{\partial U}{\partial C} = \frac{(\beta_1 + v_1) + \beta_2 + \beta_{4i} \text{ Frequency Delay}}{\beta_5 + \beta_6 \text{ Existing Toll}} \text{ for } i = 1, \dots, 5 \tag{11}$$

$$w_r = \frac{\partial U}{\partial R} / \frac{\partial U}{\partial C} = \frac{(\beta_{3i} + v_2) + \beta_{4i} \text{ Average Delay Time}}{\beta_5 + \beta_6 \text{ Existing Toll}} \text{ for } i = 1, \dots, 5 \tag{12}$$

The implied WTP for travel time for a commuter who already pays a toll can be calculated as:

$$w_t = \frac{-0.083 + v_1}{-0.738 + 0.201} \times 60 = \frac{-0.083 + v_1}{-0.537} \times 60 \tag{13}$$

Here,  $w_t$  is expressed in dollar/hour and  $v_1$  are randomly drawn values from a normal distribution with mean zero and SD 0.082. Similarly, for a commuter who already pays a toll, the following implied WTP distribution for frequency embedded travel time to avoid unexpected delay ‘5 days out of 10 days’ is:

$$w_{ft} = \frac{(-0.083 + v_1) - 0.046 - 0.028}{-0.738 + 0.201} \times 60 = \frac{(-0.083 + v_1) - 0.074}{-0.537} \times 60 \tag{14}$$

Here,  $w_{ft}$  is expressed in dollar/hour and  $v_1$  are randomly drawn values from a normal distribution with mean zero and SD 0.082. Finally, the WTP for travel time reliability can be calculated based on both the frequency and magnitude of unexpected delay. As an example, the following two equations show the implied WTP distribution for avoiding 60 and 10 min of unexpected delay ‘5 days out of 10 days’, respectively. Note that when unexpected delay is assumed to be 60 min, the WTP for travel time reliability can be expressed in dollars/hour.

$$w_{r60} = \frac{(-0.741 + v_2) - 0.028 \times 60}{-0.738 + 0.201} = \frac{(-0.741 + v_2) - 1.68}{-0.537} \tag{15}$$

$$w_{r10} = \frac{(-0.741 + v_2) - 0.028 \times 10}{-0.738 + 0.201} = \frac{(-0.741 + v_2) - 0.28}{-0.537} \tag{16}$$

$w_{r60}$  is expressed in dollar/hour,  $w_{r10}$  is expressed in dollars, and  $v_2$  are randomly drawn values from a normal distribution with mean zero and SD 0.623.

Table 5 shows the mean WTP for travel time for respondents who do not pay tolls is calculated at \$6.98/h while the mean WTP for commuters who already pay tolls is \$9.59/h. The second measure calculates WTP for frequency embedded travel time (as given in Eq. 11) which takes into account both the frequency and magnitude of unexpected delay. The mean WTP for frequency embedded travel time is calculated as high as \$17.14/hour to avoid unexpected delays ‘9 days out of 10 days’. As a comparison, this mean value is about 1.7 times higher than the mean WTP value calculated for avoiding unexpected delays ‘1 day out of 10 days’. Similar but higher values of the WTP measures are obtained for respondents who already pay tolls.

The third WTP measure shown in the table provides values for travel time reliability. As shown in the marginal utilities equations, the WTP measures for travel time reliability is a function of both the frequency and the amount of unexpected delay. The VOR also increases as the frequency of unexpected delay days increases. For example, respondents who do not pay tolls are likely to pay as high as \$7.09/h to avoid unexpected delays ‘9 days out of 10 days’ as compared to a route with unexpected delays ‘1 day out of 10 days’. The values are higher for respondents who already pay tolls. In order to show how the amount of delay affects the VOR, similar WTP values are calculated for travel time reliability with 10 min of unexpected delay, as shown in Eq. (16).

There appears to be a relationship between WTP for travel time and WTP for reliability. The ‘reliability’ increase in WTP for travel time is about equal to the frequency (or percentage) of experiencing unexpected delay. For example, the WTP for travel time is \$6.98/h, however, reliability adds \$3.27 (about 47 % of \$6.98) to avoid unexpected delays ‘5 out of 10 days’ (or to avoid unexpected delays 50 % of the time). A similar trend can be seen for the categories ‘7 out of 10 days’ and ‘9 out of 10 days’. Therefore, one can conclude that the travel time reliability increase in WTP for travel time for a route is

**Table 5** Willingness-to-pay estimates

Categories	Commuters who don't pay tolls		Commuters who pay tolls	
	Mean estimate	Lower and upper 95 % limit <sup>a</sup>	Mean estimate	Lower and upper 95 % limit <sup>a</sup>
<b>WTP for travel time</b>				
Based on usual travel time	\$6.98/h	(\$6.59, \$7.37)	\$9.59/h	(\$9.04, \$10.14)
<b>WTP for frequency embedded travel time</b>				
Avoid delay '1 day out of 10 days'	\$10.72/h	(\$10.17, \$11.27)	\$14.73/h	(\$14.18, \$15.28)
Avoid delay '3 days out of 10 days'	\$12.43/h	(\$11.88, \$12.98)	\$17.07/h	(\$16.52, \$17.62)
Avoid delay '5 days out of 10 days'	\$13.00/h	(\$12.45, \$13.55)	\$17.86/h	(\$17.31, \$18.41)
Avoid delay '7 days out of 10 days'	\$15.27/h	(\$14.72, \$15.82)	\$20.99/h	(\$20.44, \$21.54)
Avoid delay '9 days out of 10 days'	\$17.14/h	(\$16.59, \$17.69)	\$23.56/h	(\$23.01, \$24.11)
<b>WTP for travel time reliability (value of reliability in \$/h)</b>				
1 day out of 10 days	Ref.		Ref.	
3 days out of 10 days	\$1.71/h	–	\$2.35/h	–
5 days out of 10 days	\$3.27/h	(\$3.22, \$3.32)	\$4.49/h	(\$4.41, \$4.57)
7 days out of 10 days	\$5.22/h	(\$1.44, \$9.00)	\$7.65/h	(\$1.85, \$13.45)
9 days out of 10 days	\$7.09/h	(\$4.76, \$9.42)	\$9.75/h	(\$5.18, \$14.32)
<b>WTP in terms of frequency and amount of delay (value of reliability)</b>				
10 min of delay '1 out of 10 days'	Ref.		Ref.	
10 min of delay '3 out of 10 days'	\$0.28	–	\$0.39	–
10 min of delay '5 out of 10 days'	\$1.40	(\$1.32, \$1.48)	\$1.93	(\$1.85, \$2.01)
10 min of delay '7 out of 10 days'	\$1.77	(\$0.79, \$2.75)	\$2.44	(\$0.85, \$4.03)
10 min of delay '9 out of 10 days'	\$1.74	(\$1.15, \$2.33)	\$2.39	(\$1.23, \$3.55)

<sup>a</sup> The confidence intervals for WTP measures are calculated using Krinsky and Robb (1986) method when the numerator has a normally distributed parameter and the delta method is used in case there are no randomly distributed coefficients

**Table 6** Reliability ratio estimates

Categories	Mean estimate
For commuters who don't pay tolls	
1 day out of 10 days	–
3 days out of 10 days	0.24
5 days out of 10 days	0.47
7 days out of 10 days	0.75
9 days out of 10 days	1.01
For commuters who pay tolls	
1 day out of 10 days	–
3 days out of 10 days	0.25
5 days out of 10 days	0.47
7 days out of 10 days	0.80
9 days out of 10 days	1.02

proportional to the uncertainty associated with that route. This is an important finding from a policy perspective. This relationship is further reflected when reliability ratios are calculated for various levels of travel time reliability (see Table 6). The reliability ratios for different frequencies of unexpected delays vary from 0.24 to 1.02. These values fall within the range of values found in previous literature, however, it should be noted that most of the previous studies use SD as the measure of travel time variability/reliability and in our case the ratios were calculated for different levels of travel time reliability (expressed in frequency of unexpected delays). Therefore, these results could not be directly compared to any previous study.

## Discussion and conclusions

The study used a SP survey methodology to elicit commuters' route choice sensitivities toward travel time reliability. The contribution of this study lies in our effort to express travel time reliability based on two-dimensions: the frequency of unexpected delay, and the magnitude of unexpected delay. The results show that commuters prefer routes that not only have less amount of unexpected delays but are also more consistent over a period of time. In other words, the frequency of experiencing unexpected delay days is as important as unexpected delay itself.

The study also contributes to the existing literature by calculating WTP measures that correspond to different levels of frequency of unexpected delay days. Three different WTP measures are calculated, including the WTP for travel time, the WTP for frequency embedded travel time, and the WTP for travel time reliability. The frequency embedded value of time can also be seen as a combined measure of both the travel time and the travel time reliability. The WTP for travel time reliability is based on both the frequency and the amount of unexpected delays and it was found that mean estimation of WTP increases with increasing unreliability.

The WTP measures show significant heterogeneity and the mean WTP estimates are much higher for respondents who already pay tolls for their commute trips as compared to respondents who do not. This can be attributed to the fact that commuters who already pay tolls value on-time arrivals more and that's why they chose to pay higher in the first place.

Moreover, they become aware of the benefits of using tolls in a long-term. The SP survey questions defined a clear tradeoff between expected travel time and toll cost for respondents, allowing time-sensitive respondents to self-select the lower travel time (and frequency of unexpected delay) while toll sensitive respondents to compromise on travel time for a lower toll cost or not at all.

The study provides a valuable input to cost-benefit analysis and traffic and revenue studies which require scientific estimates that establish WTP. Traditionally, only the dollar value of time is used in highway revenue and toll revenue studies, however, states and agencies can gain more value if an economic VOT reliability is incorporated in these cost-benefit studies. As such, road pricing efforts should not only be geared toward increasing travel time savings but also should reduce the frequency and extent of unexpected delays. Supply side agencies can gain in terms of higher expected revenue from the tolling facilities and while commuters can expect better value for the amount of tolls they pay.

Finally, it should be noted that the external validity of our survey results may be limited. Since the study sample mostly included employed, higher than median income, college graduates, and people living in major urban metropolitan areas, due care should be given before generalizing the results to the population as a whole.

**Acknowledgments** We thank the Dwight David Eisenhower Transportation Fellowship Program for their support to conduct this research. This work was done as a part of the first author's doctoral studies at the University of Iowa. As such, the paper is drawn from the first author's PhD dissertation. We also thank the paper's reviewers for their very helpful comments.

## References

- Abdel-Aty, M., Kitamura, R., Jovanis, P.: Using stated preference data for studying the effect of advanced traffic information on drivers' route choice. *Transp. Res. Part C* **5**(1), 39–50 (1997)
- Bates, J., Polak, J., Jones, P., Cook, A.: The valuation of reliability for personal travel. *Transp. Res. Part E* **37**(2–3), 191–229 (2001). doi:[10.1016/S1366-5545\(00\)00011-9](https://doi.org/10.1016/S1366-5545(00)00011-9)
- Bierlaire, M.: An Introduction to Biogeme version 1.6. <http://www.biogeme.epfl.ch> (2008). Accessed March 2011
- Bliemer, M.C.J., Rose, J.M.: Construction of experimental designs for mixed logit models allowing for correlation across choice observations. *Transp. Res. Part B* **46**(3), 720–734 (2010). doi:[10.1016/j.trb.2009.12.004](https://doi.org/10.1016/j.trb.2009.12.004)
- Bliemer, M.C.J., Rose, J.M.: Experimental design influences on stated choice outputs: an empirical study in air travel choice. *Transp. Res. Part A* **45**(1), 63–79 (2011). doi:[10.1016/j.tra.2010.09.003](https://doi.org/10.1016/j.tra.2010.09.003)
- Carrion, C., Levinson, D.: Value of reliability: high occupancy toll lanes, general purpose lanes, and arterials. Paper Presented at the 90th Annual Transportation Research Board Conference, 23–27 Jan 2011
- Center for Urban Transportation Research: Synthesis of research on value of time and value of reliability. Florida Department of Transportation, Tallahassee (2009)
- Chen, C., Skabardonis, A., Varaiya, P.: Travel-time reliability as a measure of service. *Transp. Res. Rec.* **1855**, 74–79 (2003)
- Daly, A., Hess, S., Train, K.: Assuring finite moments for willingness to pay in random coefficient models. *Transportation*: **39**(1), 19–31 (2012)
- Devarasetty, P., Burris, M., Shaw, W.D.: Do travelers pay for managed lane travel as they claimed they would? A before-after study of Houston Katy freeway travelers. Paper presented at the 91st Annual Transportation Research Board Conference, 22–26 Jan 2012
- Emam, B.E., Al-Deek, H.: Utilizing a real life dual loop detector data to develop a new methodology for estimating freeway travel time reliability. *Transp. Res. Rec.* **1959**, 140–150 (2006)
- Federal Highway Administration. Travel time reliability: making it there on time, all the time. [http://ops.fhwa.dot.gov/publications/tt\\_reliability/](http://ops.fhwa.dot.gov/publications/tt_reliability/) (2007). Accessed 10 Dec 2011
- Hensher, D.A., Rose, J.M., Greene, W.H.: *Applied Choice Analysis: A Primer*. Cambridge University Press, Cambridge (2005)



- Hsiao, C.: Analysis of Panel Data. Cambridge University Press, Cambridge (1986)
- Krinsky, I., Robb, A.L.: On approximating the statistical properties of elasticities. *Rev. Econ. Stat.* **68**, 715–719 (1986)
- Li, Z., Hensher, D.A., Rose, J.M.: Willingness to pay for travel time reliability in passenger transport: a review and some new empirical evidence. *Transp. Res. Part E* **46**(3), 384–403 (2010)
- Lomax, T., Schrank, D., Turner, S., Margiotta, R.: Selecting travel reliability measures. <http://tti.tamu.edu/documents/TTI-2003-3.pdf> (2003). Accessed 10 Dec 2011
- Lyman, K., Bertini, R.L.: Using travel time reliability measures to improve regional transportation planning and operations. *Transp. Res. Rec.* **2046**, 1–10 (2008)
- Markowitz, H.: Portfolio selection. *J. Finance.* **7**(1), 77–91 (1952)
- McFadden, D., Train, K.: Mixed-mnl models for discrete responses. *J. Appl. Econ.* **15**(5), 447–470 (2000)
- Noland, R.B., Small, K.A.: Travel-time uncertainty, departure time choice, and the cost of morning commutes. *Transp. Res. Rec.* **1493**, 150–158 (1995)
- Noland, R.B., Small, K.A., Koskenoja, P., Chu, X.: Simulating travel reliability. *Reg. Sci. Urban Econ.* **28**(5), 535–564 (1998)
- Sikka, N.S.: Understanding travelers' route choice behavior under uncertainty. Dissertation, University of Iowa (2012)
- Small, K.A., Verhoef, E.T.: The economics of urban transportation. Routledge, New York (2007)
- Small, K.A., Noland, R.B., Chu, X., Lewis, D.: Valuation of travel-time savings and predictability in congested conditions for highway user-cost estimation. NCHRP Report 431, Transportation Research Board, National Research Council (1999)
- Small, K.A., Winston, C., Yan, J.: Uncovering the distribution of motorists' preferences for travel time and reliability: implications for road pricing. *Econometrica.* **73**(4), 1367–1382 (2005)
- Tilahun, N.Y., Levinson, D.M.: A moment of time: reliability in route choice using stated preference. *J. Intell. Trans. Syst.* **14**(3), 179–187 (2010)
- Train, K.: Discrete Choice Methods with Simulation, 2nd edn. Cambridge University Press, Cambridge (2009)
- Tversky, A., Kahneman, D.: Rational choice and the framing of decisions. *J. Bus.* **59**(4), 251–278 (1986)
- van Lint, J.W.C., van Zuylen, H.J.: Monitoring and predicting freeway travel time reliability: using width and skew of day-to-day travel time distribution. *Transp. Res. Rec.* **1917**, 54–62 (2005)
- Wardman, M.: Public transport values of time. *Trans. Policy* **11**, 363–377 (2004)

## Author Biographies

**Nikhil Sikka** obtained his PhD in Transportation Infrastructure Engineering from the University of Iowa in May, 2012. He is now working with Resource Systems Group, Inc. as a Senior Analyst in Burlington, Vermont. His main research interests are in travel behavior and demand modeling, road pricing, transportation safety analysis, and transportation economics.

**Paul Hanley** is an Associate Professor holding joint appointments in the Public Policy Center, Graduate Program in Urban and Regional Planning and the Department of Civil and Environmental Engineering at the University of Iowa. He is the Director of the Transportation Policy Research Group at the Public Policy Center, and Associate Director of the Mid-American Transportation Center. His research interests include transportation planning, traffic engineering, transportation economics, and safety analysis.