Using Empirical Data to Find the Best Measure of Travel Time Reliability

Negin Alemazkoor
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
B156 Newmark Civil Engineering Laboratory, 205 N. Mathews Ave. Urbana, IL 61801
Tel: (979)-888-4028; Email: alemazk2@illinois.edu

Mark W. Burris, Ph.D., corresponding Author
Professor
Zachry Department of Civil Engineering
Texas A&M University
3136 TAMU, College Station, TX 77843-3136
Tel. (979) 845-9885
Email: mburris@tamu.edu

Santosh Rao Danda
Senior Consultant
Steer Davies Gleave
883 Boylston Street, Boston, MA, 02116
SantoshRao.Danda@sdgworld.net

Word Count: 5387 words + 7 tables + 1 figure = 7,387

TRR Paper number: 15-1548

March 9, 2015

ABSTRACT
The value of travel time savings (VTTS) is often the largest benefit from transportation projects and has been studied extensively. Recently, additional attention has been paid to the fact that travelers also benefit from reliable travel times. The value of reliability (VOR) has usually been estimated through stated preference data or survey based revealed preference data. In this research, empirical data was used to estimate VOR.

One concern regarding estimating VOR from empirical data is the lack of a definitive measurement for reliability. Should it be the standard deviation of travel time, the 95th percentile, or another measure? Data from Katy Freeway, where travelers choose between tolled but generally more reliable lanes and free but generally less reliable lanes, were used in an attempt to find the best measurement of reliability that could lead to the best explanation of travelers' lane choice. Multinomial logit models were used to estimate travelers' lane choice based on trip attributes including travel time, many different measures of travel time reliability, and toll. Models including only travel time and toll yielded reasonable results and value of times ($2.78/hr, $9.09/hr, and $10.52/hr for off-peak, shoulder, and peak-period, respectively). However, adding reliability to the models caused many to have counter-intuitive results and it was not possible to conclude which measure is the best. Also, the results of this research suggest that reliability might not be an influential factor in lane choice decision on managed lanes, at least when travelers have reasonable knowledge of their potential travel time.

INTRODUCTION

Reliability of travel time can be described as the variability of travel time either during a day or variability from day to day. Seven sources for variability in travel times have been identified: inadequate base capacity, demand fluctuations, traffic control devices, incidents, work zones, weather and special events (*1*). Reliability of travel time has been found to be an important factor in route choice of travelers (*2, 3, and 4*). Travel time reliability is more critical for trips with time constraints, such as trips to work. For such trips delays and late arrivals may have serious consequences, but arriving early is also undesirable.

Travel time reliability is becoming more critical for travelers, shippers and transport agencies as traffic and congestion worsen. When an element is important for the transportation systems' users, it must be important for transportation planners as well and should be considered during the transportation planning process. Not considering the benefit that users gain from improved reliability might lead to sub-optimal planning decisions as a result of underestimating benefits from a transportation project.

Due to fiscal constraints on transportation infrastructure expenditures, many transportation planning agencies are examining managed lanes (MLs) as a viable option that provides travel time savings and reliability to travelers with high values of time (VOT) and high values of reliability (VOR). MLs provide travelers a tolled but generally uncongested option while the general purpose lanes (GPLs) are free but might be congested. For those agencies that invest in MLs, it is important to predict how travelers choose between MLs and GPLs. This requires a good estimation of how travelers value the travel time and reliability offered by MLs. Although VOT has been studied extensively, studying VOR is relatively new and there are many uncertainties about it.

The first question about travel time reliability is how it should be measured. A reliability measure is needed to conduct a cost/benefit analysis or a before/after study for a project which may improve reliability. Furthermore, to understand how the travelers value reliability, it is first necessary to find out how they perceive reliability. Different measurements are suggested for travel time reliability including standard deviation, variance, 90^{th} or 95^{th} percentile, percent variation, misery index, buffer index, travel time index, planning time index, shorten right range, interquartile range, and frequency that congestion exceeds some expected threshold (these will be defined in greater depth later in the paper and outlined in Table 4).

Revealed data from travelers on Katy Freeway, where travelers choose between MLs and GPLs, was used to examine which of these measures most closely resembles how travelers perceive travel time reliability. The dataset used in this research includes all travel information of those trips made on Katy Freeway by vehicles which have a transponder in April 2012. Therefore, the start time, travel time, travel length, cost (toll) and lane choice of each trip for a particular vehicle (known individually by transponder identification) on Katy Freeway in April 2012 were available. This dataset was developed from automated vehicle identification (AVI) sensors which records the transponder ID and detection time of the vehicles. Transponder IDs were randomized for use in this analysis. Therefore, it was impossible to identify who made the actual trip, but it was possible to identify specific vehicles and their trips over the month. Travel time reliability for the MLs and GPLs of Katy Freeway were calculated using different measurements of reliability. Discrete choice models were developed using these reliability measurements along with other trip attributes such as travel time and toll. The best measurements of reliability were those included in the model that best explained travelers' lane choice. As the final step, VOT and VOR were estimated.

BACKGROUND

For freeway travel, travel time can consist of two parts: free flow time when there is no (or very little) traffic and additional time due to lowered speed resulting from traffic congestion (*5*). The additional travel time can be considered travel time variation. Wong and Sussman (1973) suggested three components for variations: (1) predictable variation resulting from differences between winter and summer, days of weeks, peak hour and off peak, (2) irregular variation resulting from changes in network conditions because of an incident and (3) random variations attributed to each traveler (*6*).

Travelers may perform some adjustments to offset the added cost of predictable variations such as changing their departure time, route or mode of travel. Therefore, the unpredictable variation is particularly troublesome for travelers. Travel time reliability is directly linked to unpredictable variations: high travel time variability means high travel time unreliability. Three frameworks have been developed to understand the travel time reliability: (1) centrality-dispersion (commonly known as mean-variance), (2) scheduling delays and (3) mean-lateness. The central-dispersion approach is based on the concept that travelers want to minimize disutility from travel time and travel time unreliability; and can be formulated as shown in Equation 1:

$$\text{Minimize } \mu + \lambda \, \sigma \qquad (1)$$

Where:

μ = expected travel time.
σ = dispersion measure of travel time distribution.
λ = coefficient.

Scheduling approach is linked to departure time choice which is based on the time constraint and the cost associated with arriving early or late. Mean-Lateness approach was first introduced by Association of Train Operating Companies (ATOC) and has become the standard for analysis of reliability of rail in the UK. Among the three frameworks, centrality-dispersion has been the predominant approach for the analysis of reliability.

Data for developing these kinds of models can be stated preference data or revealed preference data. However, most research has used stated preference techniques to find the value of travel time reliability. This method has proven to be more useful than revealed preference studies as revealed data usually cannot provide the required level of detail (*2*). Black and Towriss (1993) conducted a mail back survey and verified that travel time reliability (measured as standard deviation of travel time) is a significant factor, although it was found to be valued at only 55% of the value of mean travel time (*7*). Small et al. (1999) also used mail back surveys to gather data. They used mean-variance models, scheduling models and combined models, with data on monetary cost trade-offs, to estimate value of travel time reliability. They found the reliability ratio (value of reliability/ value of time) to be 3.22, which was substantially higher than what Black and Towriss (1993) found (*8*). Concas and Kolpakov (2009) reviewed the literature on value of travel time reliability and recommended that the reliability ratio be estimated at 0.8 to 1 under ordinary circumstances. However, under non-flexible arrival constraints it could be up to 3 (*9*).

So far, there have been few studies that have used revealed preference data to estimate a value of travel time reliability. The reason could be the scarcity of alternative routes with different travel time reliability and difficulties in gathering travel time data. Lam and Small

(2001) used data from California State Route 91 (SR-91), which includes free lanes and high occupancy toll (HOT) lanes, to estimate travelers' value of travel time reliability. They collected revealed preference data through mail surveys plus travel time data was collected through loop detectors. They used two measures for centrality (mean and median) and two measures for variability (standard deviation and shorten right range). In their best model, median and shorten right range were used as measures of travel time and reliability, respectively. They found the value of travel time reliability to be \$15.12/hr for men and \$31.91/hr for women, which were 48% and 101% of the average wage rate in their sample (*4*). Small et al. (2005) used revealed preference data (collected through phone interviews and a mail survey) and stated preference data (collected through a mail survey) to investigate the value of travel time reliability. The respondents were the travelers on SR-91.Travel time data were obtained through field measurements during similar time periods as the subjects were traveling. They used the difference between 80th and 50th percentile travel time to measure travel time reliability as they found it to fit the model better than alternate measures such as standard deviation. The value of travel time reliability was found to be \$19.56/hr (85% of the average wage rate) and its heterogeneity was found to be significant (*10*).

In the two studies above, the travel time was not what respondents actually experienced. To overcome this issue, Carrion and Levinson (2013) used a different approach and designed a GPS-based study. They studied Interstate 394 corridor lanes in Minneapolis, Minnesota. In their study, 18 commuters were recruited and equipped with GPS devices and instructed to commute for two weeks on each of the three alternatives: I-394 HOT lanes, I-394 GPLs, and a signalized arterial close to the I-394 corridor. Then, travelers were asked to drive on their preferred route. The revealed data were used to develop discrete choice models to find the value of travel time reliability. They used three different measures for reliability: standard deviation, shorten right range, and interquartile range. Their estimated value of time and value of reliability were about \$8/hr. The main drawback of this approach is the small sample size as a larger sample size would be too costly (*11*).

Differences in the research approaches to estimating a value of travel time reliability are a key obstacle in comparing the results from these studies. Lint and Zuylen (2008) showed that results from using standard deviation, coefficient of variation, buffer time index and misery index are significantly different, which verifies that using different measures of reliability would lead to different results (*12*).

DATA

So far, none of the revealed preference studies has used the actual trip attributes of the travelers' trips. A unique dataset from Katy Freeway allowed authors to make discrete choice models based on travelers' lane choices and their actual trips' attributes.

Katy Freeway connects city of Katy to city of Houston. A 12-mile section of Katy Freeway has up to six GPLs and two variably priced MLs in each direction. Katy Freeway MLs provide travelers with a new commuting option, which generally requires less travel time and is more reliable, in return for paying a toll. Tolls are collected electronically at the toll plazas. Toll rates vary by the time of day. Vehicles need to have a transponder to be charged a toll and be able to use the MLs. High occupancy vehicles (HOVs) with two or more occupants and motorcycles can use MLs for free during HOV-free hours. However, HOVs and motorcycles have to pay the same toll as single occupancy vehicles (SOVs) at all other times. In order to avoid the toll during the HOV-free hours, HOVs and motorcycles need to make sure to pass the toll plazas in the HOV lane, the leftmost lane of MLs.

The Texas Department of Transportation (TxDOT) operates automated vehicle identification (AVI) sensors both on MLs and GPLs along the Katy Freeway. Figure 1 shows the location of the sensors, each number indicates a specific sensor. These sensors detect vehicles with transponders and record the transponder ID of the vehicle and time of detection. The AVI data, which was obtained from TxDOT and the Harris County Toll Road Authority (HCTRA), contains all sensor detection records for 2012. This dataset was used to identify the trips on the MLs and GPLs. Due to inevitable problems regarding working with a huge dataset, only records from April were used in this research. For April, 870,819 unique transponder IDs with 4,496,918 trips were identified. The HCTRA dataset, which contains records of all vehicles with transponders that passed toll plazas on the MLs on the Katy Freeway, was used to supplement TxDOT AVI data to better identify trips along the MLs, assign the correct toll to each trip and also better identify free trips during HOV-free hours. Toll free trips on the MLs were excluded from the analysis.

To make sure that no transponder owner could be identified using transponder IDs, each transponder ID was assigned to a unique random ID, and the original transponder IDs were deleted. Records were sorted by random ID. Therefore, all detections for a specific random ID were placed consecutively to be able to trace a trip through the freeway. The time difference between two consecutive detections for the same random ID had to be less than 10 minutes to assume that the two detections were part of a single trip. Using the time and location of the first and last detections, travel times and distance of the trips were calculated. Based on the time of detection, and the toll schedule, tolls were assigned to the trips that were detected at toll plazas. The total toll for the trips was equal to the sum of tolls paid along the trip at up to three different toll booths. Toll rates are shown in Table 1.

To develop logit models and understand how travelers choose between MLs and GPLs, it would be necessary to model the choice the traveler was making. Therefore, for each trip on the MLs, the attributes of a similar trip on GPLs was needed, and vice versa. Therefore, for each trip, an alternate trip was created for the lane set that was not chosen. Alternate trips have the same start time and pass through the same section of the freeway but on the other set of lanes. For trips on the toll lane the alternate trip is free on GPLs. For trips on the GPLs there would be a tolled trip created. The toll depends on the number of toll booths in the section of the freeway on which trip was made and the time of day.

For the alternate trip, the travel time was calculated by taking the average of travel times on the same section of the freeway on the alternative lane (lane that was not chosen) during the same 15-minute interval in which the trip was made (same 15 minute interval on the same day). When there were no trips on the alternative lane during the 15-minute interval in which trip was made, the average speeds were used. These average speeds were calculated using actual trips that occurred on these lanes during the same time frame (off-peak, shoulder and peak) over the month.

Vehicles were only detected at the sensors. Therefore, for a vehicle that had changed the lane from GPL to ML, or vice versa, along the ML segment of Katy Freeway, it was impossible to determine the exact location of the lane switch. As a result, travel time savings could not be estimated. Consequently, those trips that switched between the GPL and ML, or vice versa, were deleted from dataset. Also, free trips on MLs during HOV free hours, weekend and holiday trips were excluded from dataset.

The final dataset, which was used in this research, had two records for each trip. The two records represented the two choices for the trip: one that was made and one on the lanes not chosen. The trip parameters included in the final dataset were the random ID, lane choice, travel time, total toll paid, trip length, and a time of day indicator of peak, off-peak, or shoulder period. Lane closure and weather data were also added to see if these data would improve the models. A dataset containing information about all incidents and lane closures on Katy Freeway for 2012 was obtained from TxDOT. For April, 121 incidents were recorded and were included in the analyses. In this research, it was assumed that only trips starting at a location upstream of the incident were impacted by the incident. A weather dataset, including hourly rainfall in inches near the Katy Freeway, was obtained from the National Climatic Data Center. A variable which indicates heavy rain (rainfall greater than 0.4 inches in an hour) was added to the trip dataset. In April 2012, there were four hours with more than 0.4 inches of precipitation. However, adding lane closure data and weather data were found to have insubstantial impact on the models and did not improve the models.

DATA ANAYLYSIS

The average travel time and standard deviation of travel time for a vehicle traveling the entire 12 mile section of Katy freeway with MLs are shown in Table 2. The percentages of trips in each lane set during each time period are shown in Table 3.

Table 3 shows that the percentage of trips with a paid toll on the MLs is larger in the peak period and decreases from peak period to shoulder period and from shoulder period to off-peak period. This is likely a result of smaller travel time savings and travel time reliability improvement in the MLs versus the GPLs during the shoulder period and off-peak period, as shown in Table 2.

Several ways of measuring reliability were used in this research (see Table 4). A definition of travel time reliability is: the consistency in travel times from day-to-day across different times of the day (13). Therefore, reliability measures shown in Table 4 need to be calculated over the month for different time periods. To calculate those reliability measures, mean, standard deviation and percentiles of travel time over the month for different time periods are needed. These statistical terms should be calculated for trips with the same length. One option is to calculate these terms for the trips with the same start location and end location during the same time period over the month. However, the main goal of this research is to find travelers' value of reliability. This depends greatly on travelers' perception of reliability and it may not be realistic to assume that travelers have an estimation of reliability based on the exact start location and end location of a trip on the freeway.

To better calculate reliability measures based on travelers' overall experience on the freeway, the travel time per mile (travel time divided by trip distance) was calculated for each trip. For the trips that were made on the same lane set and during the same time interval (one hour interval for off peak periods and 30 minute interval for peak and shoulder periods) over the month, the mean, standard deviation and percentiles of the travel time per mile were calculated. Then for each trip, the per mile attributes of the trip were multiplied by the length of that trip to find the average trip travel time and calculate the measures shown in Table 4. Since different sections of Katy Freeway were found to have similar travel times per mile, this method provides an accurate estimate of the true travel time reliabilities plus provides a value that should be closer to travelers' impression of how reliable their trip is.

Correlations between time and all reliability measures were obtained for the dataset. It was found that travel time had a high correlation (correlation coefficient between 0.6 and 1) with several measures of reliability, including standard deviation, 95^{th} percentile, short right range and interquartile range. Conversely it has a low correlation (correlation coefficient between 0 and 0.3) with the coefficient of variation, travel time index, buffer time index, misery index and percent of unacceptable trips (normalized measures of reliability).

In this research, a framework similar to centrality-dispersion framework was used, which means that travel time, a measure of reliability and cost of travel were included in the utility functions. However, the actual travel time for each trip was used instead of the mean or median travel time because data for travel time for each trip was available. Since travel time information is provided to the public through media reports, displays on roadside electronic message signs, and the Houston TranStar website, it is reasonable to assume that travelers have a good estimation of travel times on both lanes. It should be noted that the logit model inherently assumes the user has knowledge of the value of the variables such as travel time and reliability. With travel times posted, the measure of reliability used here and a set toll rate, this is not a fatal assumption.

Statistical Analysis System (SAS) was used to generate multinomial discrete-choice models. The independent variables in the multinomial logit models focused on travel conditions. The traveler's characteristics were not included in the models as such data were not available. Lane-choice models were developed based on travelers' lane of choice:

$$U_{GPL} = \beta_{TT}\text{TravelTime}_{GPL} + \beta_{TTR}\text{TravelTimeReliability}_{GPL} \quad (2)$$

$$U_{ML} = \beta_{ML} + \beta_{Toll}\text{Toll} + \beta_{TT}\text{TravelTime}_{ML} + \beta_{TTR}\text{TravelTimeReliability}_{ML} \quad (3)$$

Where:

ML = Managed Lane

GPL = General Purpose Lane

TT = Travel Time

TTR = Travel Time Reliability

β = coefficient derived from the logit model

Models were developed for the whole month, the peak period only, shoulder period only, and off-peak periods only. Table 5 includes the logit models when only time and toll were included as independent variables. This model shows negative coefficients for both time and toll. In addition, the VOT obtained from the model is reasonable and increases from off-peak periods ($2.78/hr) to shoulder periods ($9.09/hr) to peak periods ($10.52/hr). The VOT and VOR were estimated from model coefficients as shown in equations 4 and 5. This indicates that travelers' VOT is higher during the peak hour which is consistent with the literature. Using the whole dataset for the entire month over the entire day, VOT was found to be $7.00/hr. This seems reasonable as only 8% of the sample chose to pay the toll.

$$VOT = \beta_{TT}/\beta_{Toll} \quad (4)$$

$$VOR = \beta_{TTR}/\beta_{Toll} \quad (5)$$

Different reliability measures were then added to the model. It was expected that time, toll and measures of (un)reliability would have negative coefficients, indicating an increase in each of them leads to a decrease in utility. However, all models had a positive coefficient for either toll, time or reliability measure for at least one time period, which is counter-intuitive.

Two innovative reliability measures were also introduced (the last two measures in Table 4). BTE (bad trip experience) is a dummy variable which indicates whether a traveler had a bad trip in his or her previous trips. For example, if a traveler experienced a bad trip on the GPLs on his fifth trip in April, the dummy variable would be one for the GPLs, indicating having a bad trip experience on that lane set, for all trips after the fifth trip. LTE (last trip indicator) is a dummy variable which shows whether a traveler's last trip was acceptable or not. For example, if a traveler had a bad trip on the GPLs on his third trip in April then on his fourth trip, the dummy variable would be one for the GPLs. Different definitions for a bad trip were tried including a trip longer than 1.4 times median travel time, 2 times median travel time and the 80th percentile travel time. Logit models including time, toll and LTI or BTE as the reliability measure yielded a positive coefficient for LTI or BTE suggesting bad trip experiences on a lane set would increase the utility for that lane set. This likely indicates inertia or unwillingness to change lane among travelers.

Different approaches were used in an attempt to overcome this issue. In one attempt, travelers who never changed their lane were excluded from the analysis. 78 percent of travelers who had more than five trips during the study period (April 2012) never changed their lane of choice. 99 percent of those travelers always used GPLs and 1 percent always used the MLs. However, excluding trips of 78 percent of travelers yielded unreasonably high VOTs and biased the dataset in favor of MLs usage.

In order to overcome the impact of unobserved factors that are the same over time for a particular traveler, a sample dataset of one trip for each traveler was created. The last trip of each traveler who had more than 5 trips in April was selected. This dataset yielded similar VOTs as were obtained when only time and toll were included in the model of all trips. When reliability measures were added to the models using this new dataset, models had a positive coefficient for either toll, time or reliability measure for at least one time period, which is counter-intuitive again.

Among all the multinomial logit models, there were several models with time, reliability and toll as independent variables that had negative coefficients for these variables. This only occurred when the dataset included all time periods (peak period, shoulder period, and off-peak period) and was not limited to one period of day. The reason might be the greater variety of toll rates, travel time savings and reliability improvements when all time periods are included in the dataset. This helps the model to better capture the VOT and VOR. Table 6 shows the VOTs and VORs obtained from these models. When an ASC was added, or the model was limited to a single time period (peak, shoulder or off peak) the resulting model would have a positive coefficient for at least one of these key variable (toll, time, reliability).

All models, except those that only model travelers who alternated their lane choice, had a reasonable likelihood ratio index. However, including only those travelers who alternated the lane they used, biases the sample and is not appropriate.

In order to understand the value of reliability obtained by models with different reliability measures and to compare them, the average value of reliability offered by the 12 mile section of the MLs in peak period was calculated for each model (see Table 7). It can be seen that the range of the value of reliability offered by the 12 mile section of the MLs is wide, ranging from 0.09 cents to 56.00 cents. Moreover, even when VORs obtained from different reliability measures have the same unit (for example $/hr), they cannot be compared directly. In Table 7, VOR obtained from the model with standard deviation (SD) as the reliability measure ($6.37/hr) seems to be larger than the VOR obtained from the model with 95th percentile of time as reliability measure ($1.98/hr). However, when value of reliability offered by MLs is calculated the latter suggests a larger value.

$$\frac{(33.23 - 22.40)\ min}{60\ min} * 1\ hr * \frac{\$1.98}{hr} = \$0.36 > \frac{(7.01 - 4.24)\ min}{60\ min} * 1\ hr * \frac{\$6.37}{hr} = \$0.29$$

Overall, it can be concluded that results from different reliability measures are considerably different and a definitive measure was not clear from the results.

The fact that many models (those not presented in table 6 and 7) failed to provide intuitive results may be due to several reasons. One reason could be the relative lack of variation in the toll schedule. Another limitation is the lack of information regarding travelers' characteristics. Also, other attributes of the GPLs and MLs, such as accessibility, were not included in the models. Those may have considerable influence on travelers' decisions. It is also likely that travelers' perception of the benefit of MLs is not limited to travel time savings and travel time reliability. This is reinforced by the fact that even during the off peak period, when travel time savings is very small, some travelers pay to use the MLs. Moreover, there is also a possibility that travelers' perception of travel time reliability may be different from all the measures that were used in this research**.**

CONCLUSIONS

The objective of this research was to find the best measure of reliability and subsequently, the value of reliability by studying travel behavior and lane choice of Katy Freeway travelers. Multinomial logit models were used to better understand how trip attributes including travel time, toll, and travel time reliability impact travelers' choice between the GPLs and MLs. When only time and toll were included in the models, reasonable VOTs were obtained. When time, toll and reliability were included in the models that examined the entire day, some reasonable results were obtained but,there was not one that was clearly the best. Examining a single period of the day (Peak, Shoulder or Off-Peak) or including the ASC invariably lead to counter-intuitive results. So, how travelers perceive reliability, or if it was even an important factor in their lane choice remained unclear. Travel time reliability may not be an influential factor in travelers' lane choice when estimations of travel times are provided for travelers through roadside electronic message signs (as is the case on Katy Freeway) or other tools.

ACKNOWLEDGMENT

The authors thank Dr. Yunlong Zhang, Dr. Michael Sherman and Dr. Dominique Lord for their helpful comments on the project. Authors appreciate the sharing of data by Texas Department of Transportation (TxDOT) and Harris County Toll Road Authority (HCTRA). However, the content of the paper reflect solely views of the authors and do not represent the opinions of TxDOT, HCTRA, Texas A&M, or any other agency or organization.

REFERENCES

1. Cambridge Systematics. *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation*. Report for Federal Highway Administration, Washington, DC. http://www.ops.fhwa.dot.gov/congestion_report/. Accessed July 21, 2014.

2. Abdel-Aty, M. A., R. Kitamura, and P. P. Jovanis. Investigating Effect of Travel Time Variability on Route Choice Using Repeated-Measurement Stated Preference Data. In *Transportation Research Record: Journal of the Transportation Research Board, No.1493,* Transportation Research Board of the National Academies, Washington, D.C., 1995, pp. 39-45.
3. Bates, J., J. Polak, P. Jones, and A. Cook. The Valuation of Reliability for Personal Travel. *Transportation Research Part E: Logistics and Transportation Review*, Vol. 37, No. 2, 2001, pp. 191-229.
4. Lam, T.C., and K.A. Small. The Value of Time and Reliability: Measurement from a Value *Pricing Experiment. Transportation Research Part E: Logistics and Transportation Review*, Vol. 37, No. 2, 2001, pp. 231–251.
5. Carrion, C., and D. Levinson. Value of Travel Time Reliability: *A Review of Current Evidence. Transportation Research Part A*, Vol. 46, No. 4, 2012, pp. 720-741.
6. Wong, H., and J. Sussman. Dynamic Travel Time Estimation on Highway Networks. *Transportation Research*, Vol. 7, No.4, 1973, pp. 355–370.
7. Black, I. G., and J. G. Towriss. *Demand Effects of Travel Time Reliability*. Centre for Logistics and Transportation, Cranfield Institute of Technology, Cranfield, United Kingdom, 1993.
8. Small, K. A., R. Noland, X. Chu, and D. Lewis. *NCHRP Report 431: Valuation of Travel-Time Savings and Predictability in Congested Conditions for Highway User-Cost Estimation*. TRB, National Research Council, Washington, D.C., 1999.
9. Concas, S., and A. Kolpakov. *Synthesis of Research on Value of Time and Value of Reliability.* Center for Urban Transportation Research, Florida Department of Transportation, Tampa, 2009.
10. Small, K.A., C. Winston, and J. Yan. Uncovering the Distribution of Motorists' Preferences for Travel Time and Reliability. *Econometrica*, Vol. 73, No.4, 2005, pp.1367-1382.
11. Carrion, C., and D. Levinson. Valuation of Travel Time Reliability from a GPS-Based Experimental Design. *Transportation Research Part C: Emerging Technologies*, Vol. 35, 2013, pp. 305-323.
12. van Lint, J. W. C., H. J. van Zuylen and H. Tu. Travel Time Unreliability on Freeways: Why Measures Based on Variance Tell Only Half of the Story. *Transportation Research Part A: Policy and Practice,* Vol. 42, No.1, 2008, pp. 258-277.
13. Operations Performance Measurement Program. *Travel Time Reliability Measures*. http://ops.fhwa.dot.gov/perf_measurement/reliability_measures/index.htm. Accessed July 21, 2014.

LIST OF TABLES

LIST OF FIGURES

TABLE 2 Toll Schedule on the Katy Managed Lanes (April 2012)

Time Period	Toll Plaza		
	At Wilcrest	At Wirt	At Eldridge
Peak Period (7–9 a.m. Eastbound and 4–6 p.m. Westbound)	$1.20	$1.20	$1.60
Shoulder (6–7 a.m. and 9–10 a.m. Eastbound and 3–4 p.m. and 6–7 p.m. Westbound)	$0.60	$0.60	$0.80
Off-Peak Period (All Other Times)	$0.30	$0.60	$0.40

Source: Harris County Toll Road Authority

TABLE 2 Average Travel Time and Travel Time Standard Deviation by Period (April 2012)

Period	Average Travel Time on MLs (min)	Average Travel Time on GPLs (min)	Standard Deviation of Travel Time on MLs (min)	Standard Deviation of Travel Time on GPLs (min)
Peak Period	13.88	19.52	4.24	7.06
Shoulder Period	11.47	14.35	2.55	5.04
Off-Peak Period	10.31	11.59	1.95	3.21

TABLE 3 Classification of Trips by Time of Day (April 2012)

Time Period	Paid Trips*		GPL Trips		Total Trips**
	Count	Percentage	Count	Percentage	
Peak Period	84,079	3.68	298,758	13.08	382,837
Shoulder	39,716	1.74	292,252	12.80	331,968
Off-Peak Period	59,358	2.60	1,509,270	66.10	1,568,628
Total Trips	183,153	8.02	2,100,280	91.98	2,283,433

** Paid trips on the MLs made by SOVs and HOVs during non-HOV-free hours*

*** Total trips excludes trips made by vehicles without transponder IDs, trips on the HOV lanes during HOV-free hours, and trips detected on both MLs and GPLs in the 12 mile portion of the freeway that includes MLs.*

TABLE 4 Reliability Measures

Reliability Measure	Description	Equation
Standard Deviation (SD)	Measures the extent of dispersion of travel time	$\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$
Coefficient of Variation (CV)	Provides normalized measure of dispersion	$CV = \frac{SD}{\mu}$
95th Percentile	Indicates the value below which 95 percentage of travel times fall	
Shorten Right Range (SRR)	Shows delay for the heaviest travel condition	90th percentile travel time - median travel time
Interquartile Range (IR)	Disregards extreme travel times and measure overall travel time variability	75th percentile - 25th percentile travel time
Travel Time Index (TTI)	Compares mean time it takes to travel to free flow conditions	$\frac{Average\ travel\ time}{Free\ flow\ travel\ time}$
Buffer Time Index (BTI)	Indicates the extra time that must be added to average travel time when planning trips to ensure on-time arrival	$\frac{95^{th}\ percentile\ - Average\ travel\ time}{Average\ travel\ time}$
Planning Time Index (PTI)	Total time needed to plan for an on-time arrival 95% of the time	$\frac{95^{th}\ percentile\ travel\ time}{Free\ flow\ travel\ time}$
Misery Index (MI)	Measures how bad are the worst trips	$\frac{Average\ travel\ time\ for\ the\ longest\ 20\%\ of\ trip\ - Average\ travel\ time}{Average\ travel\ time}$
Percent of Trips with Unacceptable Delays (PT)	Percent of trips with travel time greater than the median travel time plus 20 percent of the median	
Bad Trip Experience	Shows if traveler had any unacceptable trip in his/her previous trips	
Last Trip Indicator	Shows if traveler's last trip was unacceptable	

TABLE 5 Logit Models with Time and Toll as Independent Variables

Variable	Coefficient			
	All Month	**Peak Period**	**Shoulder**	**Off-Peak**
Model: $U_{ML} = B_1 \times time + B_2 \times toll$, $U_{GPL} = B_1 \times time + B_2 \times toll$				
Time	−0.23*	−0.10*	−0.20*	−0.31*
Toll	−1.97*	−0.57*	−1.32*	−6.68*
VOT ($/hr)	7.00	10.52	9.09	2.78

**Statistically significant at 0.05 significance level ($p<0.05$).*

TABLE 6 VOT and VOR Obtained from Intuitive Logit Models

Variable	Coefficient	VOT	VOR	Correct Estimations	R^2_{McF}*	Consideration
Model: $U_{ML} = B_1 \times time + B_2 \times SD + B_3 \times toll$, $U_{GPL} = B_1 \times time + B_2 \times SD + B_3 \times toll$						
Time	−0.19	$5.51/hr	$6.37/hr	91%	0.263	Standard deviation (SD) of time and time are highly correlated.
SD	−0.22					
Toll	−2.07					
Model: $U_{ML} = B_1 \times time + B_2 \times 95th + B_3 \times toll$, $U_{GPL} = B_1 \times time + B_2 \times 95th + B_3 \times toll$						
Time	−0.19	$5.38/hr	$1.98/hr	91%	0.261	95th percentile of time and time are highly correlated.
95th Percentile	−0.07					
Toll	−2.12					
Model: $U_{ML} = B_1 \times time + B_2 \times IR + B_3 \times toll$, $U_{GPL} = B_1 \times time + B_2 \times IR + B_3 \times toll$						
Time	−0.11	$2.35/hr	$17.08/hr	89%	0.319	Interquartile range of time and time are highly correlated.
IR	−0.80					
Toll	−2.81					
Model: $U_{ML} = B_1 \times time + B_2 \times SRR + B_3 \times toll$, $U_{GPL} = B_1 \times time + B_2 \times SRR + B_3 \times toll$						
Time	−0.20	$5.82/hr	$2.04/hr	91%	0.259	Short right range of time and time are highly correlated.
SRR	−0.07					
Toll	−2.06					
Model: $U_{ML} = B_1 \times time + B_2 \times PT + B_3 \times toll$, $U_{GPL} = B_1 \times time + B_2 \times PT + B_3 \times toll$						
Time	−0.22	$6.60/hr	Value of reducing unacceptable trips by 10 percent = 3.3 cents.	91%	0.257	
PT	−0.67					
Toll	−2.00					
Model: $U_{ML} = B_1 \times time + B_2 \times CV + B_3 \times toll$, $U_{GPL} = B_1 \times time + B_2 \times CV + B_3 \times toll$						
Time	−0.14	$24.00/hr	Value of reducing coefficient of variation by 1 percent = 5.4 cents.	61%	0.030	Only trips of travelers who alternated their lane choice were included in the dataset.
CV	−1.89					
Toll	−0.35					
Model: $U_{ML} = B_1 \times time + B_2 \times MI + B_3 \times toll$, $U_{GPL} = B_1 \times time + B_2 \times MI + B_3 \times toll$						
Time	−0.15	$23.68/hr	Value of reducing misery index by 1 percent = 4.0 cents.	62%	0.031	Only trips of travelers who alternated their lane choice were included in the dataset.
MI	−1.51					
Toll	−0.38					
Model: $U_{ML} = B_1 \times time + B_2 \times PT + B_3 \times toll$, $U_{GPL} = B_1 \times time + B_2 \times PT + B_3 \times toll$						
Time	−0.14	$22.70/hr	Value of reducing unacceptable trips by 1 percent = 4.0 cents.	61%	0.028	Only trips of travelers who alternated their lane choice were included in the dataset.
PT	−1.49					
Toll	−0.37					

Model: $U_{ML}= B_1\times time + B_2\times MI + B_3\times toll$, $U_{GPL}= B_1\times time + B_2\times MI + B_3\times toll$						
Time	−0.29	$7.66/hr	Value of reducing misery index by 10 percent = 0.44 cents.	91%	0.268	Only the last trips of travelers with more than 5 trips were included in the dataset.
MI	−0.10					
Toll	−2.27					
Model: $U_{ML}= B_1\times time + B_2\times PT+ B_3\times toll$, $U_{GPL}= B_1\times time + B_2\times PT + B_3\times toll$						
Time	−0.28	$7.17/hr	Value of reducing unacceptable trips by 1 percent = 0.7 cents.	91%	0.270	Only the last trips of travelers with more than 5 trips were included in the dataset.
PT	−1.64					
Toll	−2.34					

* R^2_{McF} *is "McFadden's likelihood-ratio index".*

TABLE 7 Average Value of Reliability Offered by 12 Mile Section of the MLs in Peak Period

Variable	**Coefficient**	**VOT**	**VOR**	**MLs Reliability**	**GPLs Reliability**	**Value of Reliability Offered by MLs**
Model: $U_{ML}= B_1 \times time + B_2 \times SD + B_3 \times toll$, $U_{GPL}= B_1 \times time + B_2 \times SD + B_3 \times toll$						
Time	−0.19	$5.51/hr	$6.37/hr	4.24 min	7.01 min	29.41 cents
SD	−0.22					
Toll	−2.07					
Model: $U_{ML}= B_1 \times time + B_2 \times 95th + B_3 \times toll$, $U_{GPL}= B_1 \times time + B_2 \times 95th + B_3 \times toll$						
Time	−0.19	$5.38/hr	$1.98/hr	22.40 min	33.23 min	35.74 cents
95^{th} Percentile	−0.07					
Toll	−2.12					
Model: $U_{ML}= B_1 \times time + B_2 \times IR + B_3 \times toll$, $U_{GPL}= B_1 \times time + B_2 \times IR + B_3 \times toll$						
Time	−0.11	$2.35/hr	$17.08/hr	2.89 min	4.84 min	55.51 cents
IR	−0.80					
Toll	−2.81					
Model: $U_{ML}= B_1 \times time + B_2 \times SRR + B_3 \times toll$, $U_{GPL}= B_1 \times time + B_2 \times SRR + B_3 \times toll$						
Time	−0.20	$5.82/hr	$2.04/hr	10.25 min	15.26 min	17.03 cents
SRR	−0.07					
Toll	−2.06					
Model: $U_{ML}= B_1 \times time + B_2 \times PT + B_3 \times toll$, $U_{GPL}= B_1 \times time + B_2 \times PT + B_3 \times toll$						
Time	−0.22	$6.60/hr	Value of reducing unacceptable trips by 10 percent = 3.35 cents.	16.7%	30.8%	4.72 cents
PT	−0.67					
Toll	−2.00					
Model: $U_{ML}= B_1 \times time + B_2 \times CV + B_3 \times toll$, $U_{GPL}= B_1 \times time + B_2 \times CV + B_3 \times toll$*						
Time	−0.14	$24.00/hr	Value of reducing coefficient of variation by 1 percent = 5.4 cents.	26.6%	32.1%	29.70 cents
CV	−1.89					
Toll	−0.35					
Model: $U_{ML}= B_1 \times time + B_2 \times MI + B_3 \times toll$, $U_{GPL}= B_1 \times time + B_2 \times MI + B_3 \times toll$*						
Time	−0.15	$23.68/hr	Value of reducing misery index by 1 percent = 4.0 cents.	38.6%	48.5%	39.60 cents
MI	−1.51					
Toll	−0.38					
Model: $U_{ML}= B_1 \times time + B_2 \times PT + B_3 \times toll$, $U_{GPL}= B_1 \times time + B_2 \times PT + B_3 \times toll$*						
Time	−0.14	$22.70/hr	Value of reducing unacceptable trips by 1 percent = 4.0 cents.	17.0%	31.0%	56.00 cents
PT	−1.49					
Toll	−0.37					

Model: $U_{ML}= B_1\times time + B_2\times MI + B_3\times toll$, $U_{GPL}= B_1\times time + B_2\times MI + B_3\times toll$**						
Time	−0.29	$7.66/hr	Value of reducing misery index by 10 percent = 0.44 cents.	44.0%	46.0%	0.09 cents
MI	−0.10					
Toll	−2.27					
Model: $U_{ML}= B_1\times time + B_2\times PT + B_3\times toll$, $U_{GPL}= B_1\times time + B_2\times PT + B_3\times toll$**						
Time	−0.28	$7.17/hr	Value of reducing unacceptable trips by 1 percent = 0.7 cents.	13.2%	30.2%	11.90 cents
PT	−1.64					
Toll	−2.34					

* *Only those travelers who alternated their lane choice were included.*

** *Only the last trips of travelers with more than 5 trips were included in the dataset.*

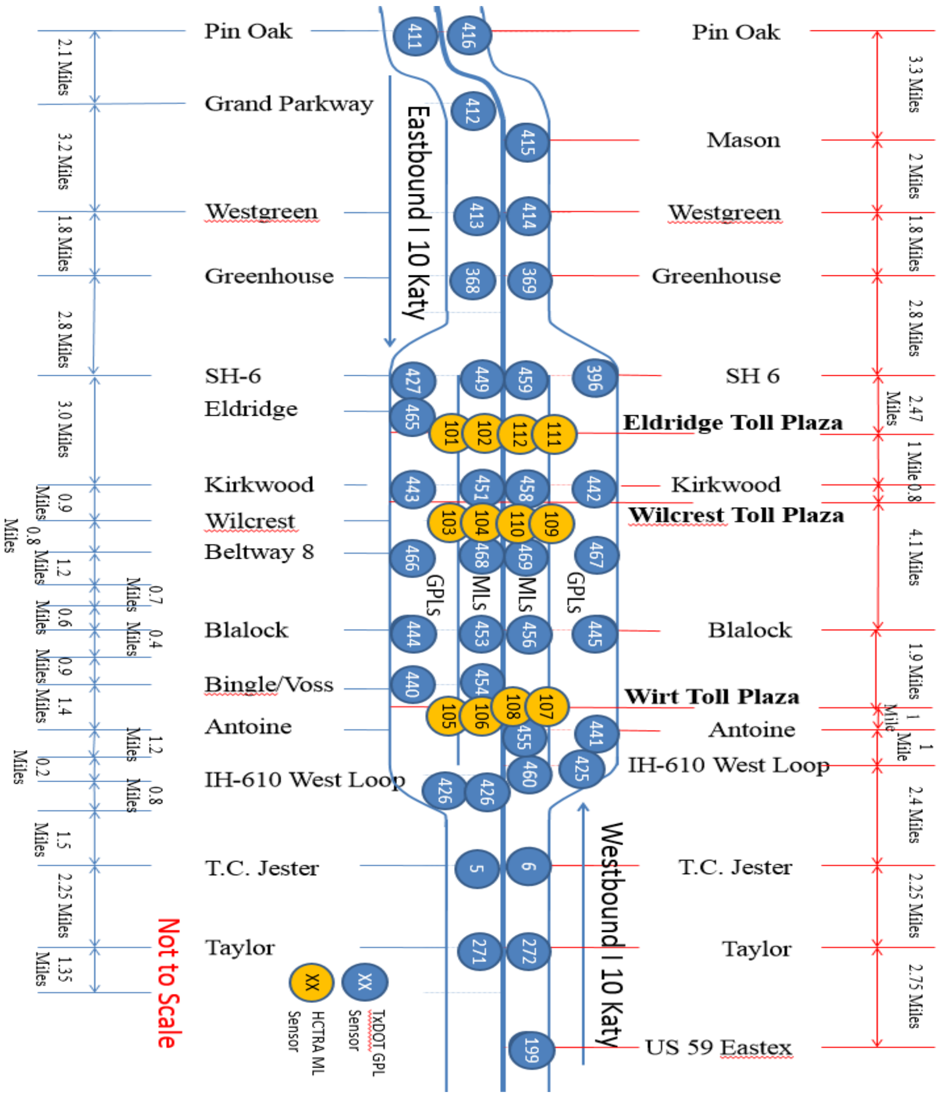

FIGURE 1 Katy Freeway AVI Sensor Location