Measuring value of travel time and travel time variability in the presence of managed lanes: results from a pilot stated preference survey on the Capital Beltway

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Managed lanes are roadways that have additional requirements placed on their usage in an effort to maintain reliable, uncongested flow. This concept is already gaining use in some parts of the United States where vehicles that do not meet the minimum vehicle occupancy requirements are allowed to use the high occupancy vehicle (HOV) lane with the payment of a fee, leading to the term, high occupancy toll (HOT) lanes. This study collects data on behavioral responses to managed lanes and in particular quantifies a traveler's value of time in the hypothetical scenario that managed lanes are applied on the Maryland side of the Capital Beltway. The main purpose is to provide a data collection and evaluation framework to assess potential projects. Two stated preference (SP) surveys have been designed and executed. The first analyzes choice across normal lanes, HOT and HOV, proposing different components of travel time. The second is developed in a context of departure time shift and proposes uncertainty as a range. Results show that the second experiment was more successful in recovering work and non-work values of travel time, delivers significant results for the uncertainty coefficients, and reinforces the finding that later departure time is perceived more negatively than earlier departure time.

Keywords: Value of time, Travel time variability, Managed lanes, HOT lanes, Stated preference

Introduction

Road pricing has been advocated as an efficient travel demand management strategy to alleviate congestion since the seminal work by Pigou (1920) and Knight (1924) (see Lindsey (2006) for recent reviews). More recently, toll pricing has received great interest among policy makers and public agencies due to its potential to improve network efficiency and to generate revenues to pay for transportation improvements. Analytical studies, such as Arnott *et al.* (1998), have found that dynamic toll pricing generally yields greater efficiency gains than static toll pricing because the dynamic tolls reduce queuing delays by altering travelers' departure times as well as routes. The I-495 Express Lanes project in Virginia and the Inter-county Connector in Maryland are examples of recent road pricing structures with dynamic tools. Daily traffic volumes are governed by individual trip-makers' perceived time and cost saving in terms of their value of travel time (VOT). Pricing schemes are also advocated as a strategy that potentially provides incentive to travelers with more flexible departure time to travel during the off peak period, thereby shifting/spreading peak travel demand and improving travel time reliability.

One promising approach in implementing road pricing is to convert existing under-utilized high occupancy vehicle (HOV) lanes to high occupancy toll (HOT) lanes. The HOT Lanes Project and the Inter-county Connector in Virginia and Maryland are examples of recent road pricing structures. High occupancy toll lanes[1] are a special case of road pricing where HOV facilities are open to lower-occupancy vehicles upon payment of a fee or toll (Goodman *et al.*, 1998). High occupancy toll lanes are often characterized as a commodity that offers faster,

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[1] The reader is referred to Börjesson *et al.* (2012), Halvorson *et al.* (2006), and Viti *et al.* (2003) for more recent empirical and theoretical work on HOT and tolling schemes.

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safer, and more reliable travel time for drivers who are willing to pay (WTP) to access it. Examples of US cities with functioning HOT lanes are Miami (FL), Seattle (WA), Denver (CO), San Diego (CA), Atlanta (GA), Salt Lake City (UT), Houston (TX), and Minneapolis (MN), with more under construction or planned (Los Angeles County Metropolitan Transportation Authority 2010). Congestion pricing is becoming a more attractive alternative for agencies to deal with high congestion levels and underused HOV lanes. Nevertheless, the key questions are how much drivers are WTP to save time and/or reduce travel time variability, and whether travel time reliability influences the behavior of travelers.

Given that these infrastructures rely on a toll pricing scheme, its daily traffic volumes are governed by individual trip-makers' perceived time and cost saving in terms of their VOT[2]. Pricing schemes are also advocated as a strategy that potentially provides incentive to travelers with more flexible departure time to travel during off peak period, thereby shifting/spreading peak travel demand and improving travel time reliability.

Jackson and Jucker (1982) asked respondents to make a choice between a journey that always has a constant duration and a journey which has a shorter time, but a possibility of a delay of 5 min once a week. Although suitable for its time, this methodology lacked variation in the alternatives and respondents could not easily understand the questions. Senna (1994) improved Jackson and Jucker framework in his research about the effect of travel time variability on VOT of Assis' corridor users, in Porto Alegre, Brazil. For this, he used a stated preference (SP) approach with three levels of mean travel time, travel time variability, and boundary values for cost (related to the selected travel time and variability). The respondents were presented trip customized scenarios, with one scenario in which travel time shows great regularity and another that offers different levels of mean travel time and variability. The respondents then selected from a five-level qualitative scale that ranged from "Definitely choose A" to "Definitely choose B." His results indicated that commuters with fixed arrival times were risk-prone whereas commuters with flexible arrival times were risk-averse. In addition, regardless of their arrival time, non-commuters were risk-averse, where risk is to be understood as getting to the destination later than expected.

Calfee and Winston (1998) used SP models to estimate the value that automobile commuters are WTP to save travel time on congested roads. Each respondent was presented with 13 alternatives that described a commute trip, including congested and uncongested travel time, travel cost (typically in terms of toll), and an indication of whether trucks were allowed on the road. The respondent was then asked to rate each alternative and to rank them (with no ties allowed). Separate samples of commuters were drawn for each of the 13 commuting road pricing scenarios. Therefore respondents stated their preferences in the context of a single scenario. Calfee and Winston found that the WTP was low ($3·00–$5·50 per h) and surprisingly insensitive to travel conditions.

Based on Swedish pilot studies of VOT estimation, Börjesson and Algers (2011) concluded that web-based and computer-assisted data collection yielded less random error in SP surveys when compared to telephone and paper-based surveys, mainly because it allows tailoring of the surveys to each respondent. Bates *et al.* (2001) developed a computer-based survey to assess rail travel time reliability. The survey included three SP games. The first focused on the flexibility of the trip schedule based on departure time, arrival time and fare. The second game addressed punctuality/reliability. Games one and two are presented at the planning stage of the trip (i.e. pre-trip). The third game dealt with en-route delays and the trade-offs between cost and mitigation of delay. Although they do not provide a value of reliability, due to the nature of the problem (i.e., difficulty to adjust departure time, given limited alternatives in transit), the authors present a concise framework to present complex SP games and variables (such as variability). They show that in the case of complex games, consistency in presentation and an adequate increase in difficulty by game help respondents to better understand the questions.

Most of the attempts to estimate choice models that include travel time variability variables use SP techniques (Hollander, 2006). Hollander modeled the attitudes of bus users to travel time variability and their departure time choice considerations. He used data collected via an Internet-based SP survey conducted at the city of York, England in 2004. The survey consisted of nine questions. In each question, the respondent is asked to consider two alternative bus services, each with a specific fare, departure time from home, and distribution of five possible arrival times to the destination (i.e. variability). Travel times were not explicitly stated; instead they could be deduced from the series of vertical bars that contain scaled information on the departure and arrival time. Hollander's results indicate that bus users seem to be bothered by the effects of variability on their extent of lateness and earliness to the destination, not by variability itself. Asensio and Matas (2008) reached the same conclusion from an SP dataset from Barcelona, Spain.

Finkleman *et al.* (2011) conducted a WTP study in the Greater Toronto Area, Canada. The study was based on common trip characteristics (i.e. travel speed and trip distance) and introduces "trip urgency" as a factor. For facilities with HOT lanes parallel to the main roadway, their results indicated travelers were WTP $10·30 per h for a trip on the HOT lane. On the other hand, for the least urgent trips, their WTP decreased to $2·70 per h. As expected, they found that trip urgency plays a significant role on the travelers' decision to pay for admission to the HOT lanes.

Börjesson (2008) estimated a mixed logit model of departure time choice that incorporates travel time variability. Her analysis was based on joint RP and SP data of congestion charging trial in Stockholm during 2006. The proposed joint model of departure time and mode choice consisted of 21 alternatives from RP and SP surveys. The results indicated that SP data was less

[2] The reader is referred to Bates *et al.* (2001), Hollander (2006), Li *et al.* (2010), and Noland and Polak (2002) for more comprehensive coverage of the general theory and empirical work in the area of traveler's value of travel time reliability.

trustworthy for trip timing analysis and forecasting, presumably due to temporal differences in RP and SP choice situations. The evaluation found no evidence that the car riders changed their departure time to any tangible degree. Instead, the most common adaptation was to switch to public transport. Conversely, Sibdari and Jeihani (2009) showed that dynamic tolls affect travelers' route and departure time choice, using simulated scenarios of I-15 in San Diego (CA). Moreover, if departure time is to be changed, results from a study in Switzerland showed that travelers are more sensitive to late arrival times compared to early departure times, as confirmed by the absolute value of the penalty for late departure being twice as high as the penalty for early departure (Vrtic *et al.*, 2009).

Hess *et al.* (2007) study sensitivity of time and mode switching to understand whether and how travelers will change the timing of their journeys. In particular, their analysis aims at determining the relative sensitivity of mode and time of day choice to changes in travel times and costs. Results are obtained and compared across different travel segments and SP data sets (two in the UK, one in the Netherlands). Arellana *et al.* (2012) have recently introduced a procedure that generates survey design to obtain data suitable for estimation of departure time choice. They propose a Bayesian efficient SP-off-RP step design that accommodates interdependence among attribute levels. Variables presented to respondents include: departure time to work, travel time to work (usual and once a week), comfort, and travel cost. A preliminary application was developed for the city of Santiago, Chile where local authorities are considering different travel demand management strategies.

The purpose of this research is to contribute to the literature on how to measure the effect of departure time and travel time reliability on travelers' value of time and acceptability of HOT lanes. To do this, two stated choice experiments are proposed: the first concentrates on the source of travel time variability (congestion and accidents) and the second focuses on varying departure times. As a secondary purpose, these two survey schemes are evaluated and analyzed to determine its capacity to successfully measure the previously mentioned effects using both parametric and non-parametric mixed logit models. Results show that the survey design was able to capture individual preferences for cost and time trade-offs. Additionally, the non-parametric models produced more realistic parameter estimates as well as value of time estimates.

Mixed logit model

Discrete choice models are used to model individual preferences. Consider a set of N individuals with each having to choose one alternative within a finite set $A(n)$. A utility, U_{nj} is associated with each alternative A_j in $A(n)$, as perceived by individual n. Relying on econometric theory, the models also assume that individuals aim to maximize their utility, but that the modeler cannot observe all of the components. Instead, the utility U_{nj} is decomposed as the sum of a deterministic part $V_{nj}(\beta)$, where β is a vector to estimate, and a random, unobserved part ε_{nj}. The probability choice is then

$$L_{nj}(\beta)=P\left[V_{nj}(\beta)+\varepsilon_{nj}\geq V_{na}(\beta)+\varepsilon_{na},\forall a\in A(n)\right] \quad (1)$$

In the rest of this paper, only linear-in-parameter utilities are considered (as is standard practice in transportation field). The probability expression is dependent on the distributional assumption for ε_{nj}. When the ε_{nj}s are assumed to be i.i.d. Gumbel variables amongst the individuals and alternatives, traditional logit probability is obtained. This study adopts a mixed logit formulation where the assumption that β is a constant vector is relaxed; parameters are considered to be random vectors with cumulative distribution function $F_B(\beta)$ so that the probability choice L_{nj} is now conditional on the realization β, and the unconditional probability is

$$P_{nj}=E_{\beta}\left[L_{nj}(\beta)\right]=\int L_{nj}(\beta)dP_{\beta}(\beta) \quad (2)$$

Assuming that β is derived from a random vector γ and a parameter vector θ, denoted as $\beta=\beta(\gamma,\theta)$, then $L_{nj}(\beta)$ becomes $L_{nj}(\gamma,\theta)$. The probability choice is then given by

$$P_{nj}(\theta)=\int L_{nj}(\gamma,\theta)\phi(\gamma,\theta)d\gamma \quad (3)$$

where $\phi(\gamma,\theta)$ is the density of β (Train, 2009). In the case when the same individual can express several choices, each individual's sequence of choices $y_n=(j_{n1},\ldots j_{nT_n})$ is observed, which are assumed to be correlated, and thus qualify the data as panel data. A simple way to accommodate this situation is to assume the heterogeneity is present on the population level only, but not on the individual level. The probability to observe the individual's choices is then given by the product of logit probabilities $L_{nj_{nt}}$ (Revelt and Train, 2000), as expressed in (Arnott *et al.*, 1998)

$$P_{ny_n}(\theta)=\int\left(\prod_{t=1}^{T_n}L_{nj_{nt}}(\gamma,\theta)\right)\phi(\gamma,\theta)d\gamma \quad (4)$$

The parameters θ are estimated by maximizing the loglikelihood function

$$LL(\theta)=\ln\sqrt[N]{\prod_{n=1}^{N}P_{nj_n}(\theta)}=\frac{1}{N}\sum_{n=1}^{N}P_{nj_n}(\theta) \quad (5)$$

Non-parametric mixed logit

Mixed logit models based on non-parametric random coefficients allow for the estimation of taste heterogeneity without imposing strong assumptions on the underlying distributions. They are gradually replacing discrete treatments of the parameters that could lead to arbitrary population segmentation. In this approach, each component of the random vector inherent in the mixed logit function is itself random; if independence between these components is assumed, then each component can be considered separately. If X is a univariate random distribution, a well-known technique to generate draws from its distribution consists in sampling a uniform [0,1] and in applying the inverse cumulative distribution function F_X^{-1} to these draws. It is furthermore assumed that the random variable X has a bounded support based on B-spline functions (Bastin *et al.*, 2010). The bounded support assumption is not unduly restrictive because extreme behavior, corresponding to values of X tending to plus or minus infinity, is usually undesirable. In many practical cases the bounded support assumption can be an advantage rather than a drawback.

A B-spline function of degree p is a polynomial function of degree p, defined on the interval $[a,b]$ that can be expressed as a linear combination of $n+1$ basis functions $N_{i,p}(u)$ as follows

$$C(u)=\sum_{i=0}^{n}P_i N_{i,p}(u) \tag{6}$$

The coefficients P_0, P_1, …, P_n are called the control points, and u is the knot vector ($u_0=a$, u_1, …, $u_m=b$). The basis functions can be constructed by recurrence on the degree p

$$N_{1,0}=\begin{cases}1 & if\ \ u\in[u_i,u_{i+1}] \\ 0 & otherwise\end{cases}. \tag{7}$$

and

$$N_{i,p}=\frac{u-u_i}{u_{i+p}-u_i}N_{i,p-1}(u)+\frac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}}N_{i+1,p-1}(u) \tag{8}$$

such that n is equal to $m-p-1$.

The knot vector chosen for the purpose of this paper is the non-periodic (clamped or open) knot vector that takes the form

$$U=\left\{\underbrace{a,\cdots,a}_{p+1},u_{p+1},\cdots,u_{m-p-1},\underbrace{b,\cdots,b}_{p+1}\right\} \tag{9}$$

where the first and last knots have the multiplicity of $p+1$.

This study considers cubic B-spline and therefore p is set equal to 3.

Survey design

In order to study characteristics of travelers' behavior on managed lanes, a dedicated SP survey has been designed. The survey was conducted on the Maryland side of the Capital Beltway (I-495) to capture the responses of potential regional drivers to the possibility of converting a lane of the Capital Beltway to HOT operation. Changes in congestion and travel time reliability as well as shifts in

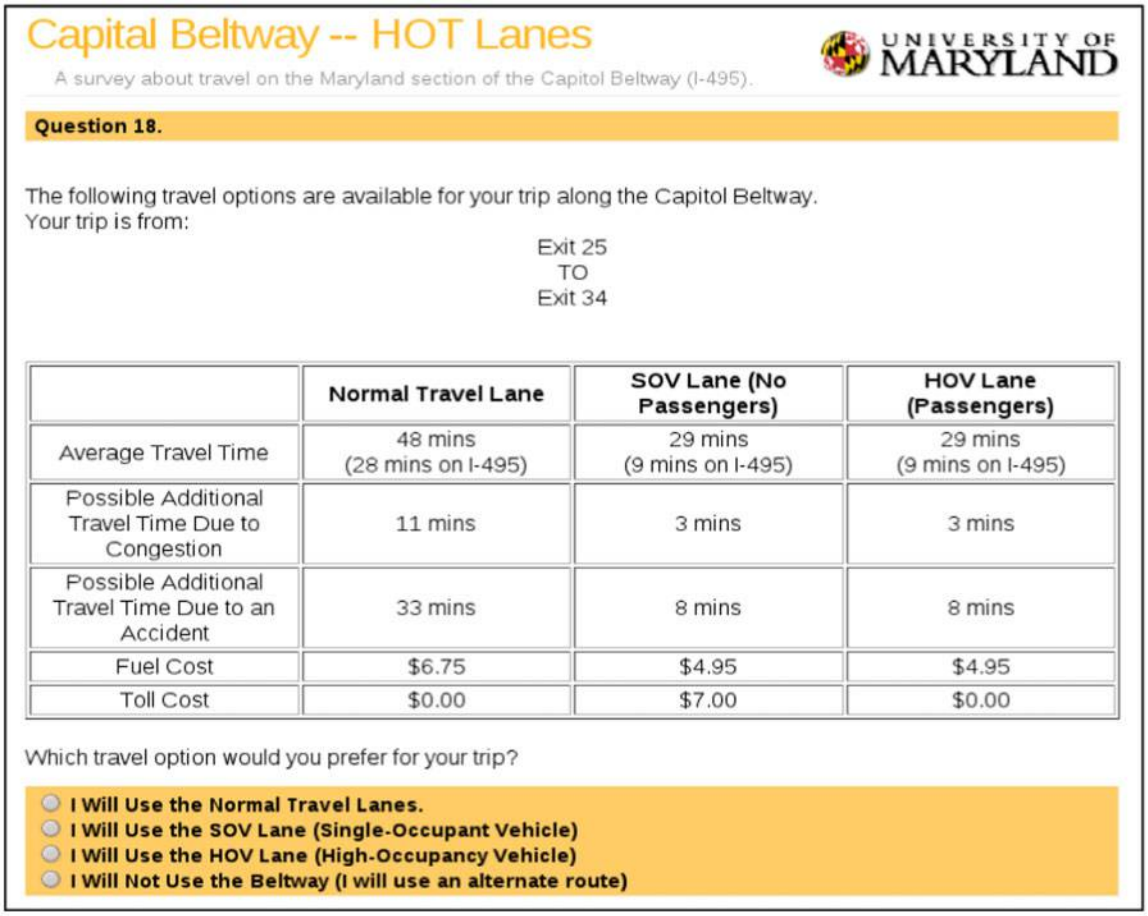
Table 1 Survey characteristics and methodology

Time frame	21–25 March 2011 and 23–27 May 2011
Target population	Potential high occupancy toll (HOT) users
Sampling frame	Current I-495 users with internet
Sample design	Flyers distributed at randomly selected exits of I-495
Mode of administration	Self-administered
Computer assistance	Computer-assisted self-interview (CASI) and web-based survey
Reporting unit	1 person age 18 or older per household reports for the entire household
Time dimension	Cross-sectional survey with hypothetical stated preference (SP) experiments
Frequency	2 4-day phases of flyers distribution
Levels of observation	Household, vehicle, and person

Table 2 Stated preference (SP) experiment 1 attributes and levels

Variable	Normal lane	High occupancy toll (HOT)	High occupancy vehicle (HOV)
Normal travel time (entire trip)	$OT+TT_{min}+CT\times0{\cdot}3$	$OT+(TT_{min}+CT\times0{\cdot}1)\times1{\cdot}1$	
	$OT+(TT_{min}+CT\times0{\cdot}3)\times1{\cdot}4$	$OT+(TT_{min}+CT\times0{\cdot}1)\times0{\cdot}9$	
	$OT+(TT_{min}+CT\times0{\cdot}3)\times1{\cdot}8$	$OT+(TT_{min}+CT\times0{\cdot}1)\times0{\cdot}7$	
Normal travel time (on I-495)	$(TT_{min}+CT\times0{\cdot}3)$	$(TT_{min}+CT\times0{\cdot}1)\times1{\cdot}1$	
	$(TT_{min}+CT\times0{\cdot}3)\times1{\cdot}4$	$(TT_{min}+CT\times0{\cdot}1)\times0{\cdot}9$	
	$(TT_{min}+CT\times0{\cdot}3)\times1{\cdot}8$	$(TT_{min}+CT\times0{\cdot}1)\times0{\cdot}7$	
Congested travel time (trip and I-495)	$D\times1{\cdot}33$	$D\times0{\cdot}4$	
	$D\times1{\cdot}92$	$D\times0{\cdot}84$	
	$D\times2{\cdot}50$	$D\times1{\cdot}33$	
Uncertainty travel time (trip and I-495)	$D\times1{\cdot}53$	$D\times0{\cdot}52$	
	$D\times2{\cdot}80$	$D\times0{\cdot}90$	
	$D\times3{\cdot}75$	$D\times1{\cdot}53$	
Fuel cost	$FC\times1{\cdot}10$	$FC\times1{\cdot}10$	
	$FC\times1{\cdot}25$	$FC\times1{\cdot}20$	
	$FC\times1{\cdot}50$	$FC\times1{\cdot}30$	
Toll cost/$	0·00	2·00	0·00
		4·00	
		7·00	

CT: $TT_{max}-TT_{min}$; *D*: difference in exit numbers for the trip; OT: $ST-TT_{min}$; FC: fuel cost; TT_{min}: shortest travel time experienced on the whole trip in minutes; TT_{max}: longest travel time experienced on the whole trip in minutes; and ST: shortest travel time experienced on the beltway in minutes.



Capital Beltway -- HOT Lanes

A survey about travel on the Maryland section of the Capitol Beltway (I-495).

UNIVERSITY OF MARYLAND

Question 18.

The following travel options are available for your trip along the Capitol Beltway.
Your trip is from:

Exit 25
TO
Exit 34

	Normal Travel Lane	SOV Lane (No Passengers)	HOV Lane (Passengers)
Average Travel Time	48 mins (28 mins on I-495)	29 mins (9 mins on I-495)	29 mins (9 mins on I-495)
Possible Additional Travel Time Due to Congestion	11 mins	3 mins	3 mins
Possible Additional Travel Time Due to an Accident	33 mins	8 mins	8 mins
Fuel Cost	$6.75	$4.95	$4.95
Toll Cost	$0.00	$7.00	$0.00

Which travel option would you prefer for your trip?

- **I Will Use the Normal Travel Lanes.**
- **I Will Use the SOV Lane (Single-Occupant Vehicle)**
- **I Will Use the HOV Lane (High-Occupancy Vehicle)**
- **I Will Not Use the Beltway (I will use an alternate route)**

1 Stated preference (SP) experiment 1: web interface

departure time were analyzed. The questionnaire was designed as a web-based survey with respondents recruited by distributing flyers at several exit locations along I-495. Information on the flyer contained the website address and the questionnaire instructions to guide respondents in answering the questionnaire. The sample population consisted of car drivers traveling on I-495 during weekday extended peak periods (8:00 AM–11:00 AM and 3:30 PM–6:00 PM) on 21–25 March and 23–27 May 2011. Table 1 summarizes the characteristics and methodology of the survey. A total of 200 respondents from a sample of 4000 who received the flyers responded to the questionnaire, which resulted in an overall response rate of 5%. Within the 200 responded surveys, 173 of the respondents completed the survey, which resulted in an effective sample size of 173 observations for the model estimation.

The questionnaire consisted of three parts: socioeconomic and vehicle ownership, recent trip, and stated preference (SP) questions. The descriptions for each part of the survey are described next.

Socioeconomic and vehicle ownership

This section gathered socioeconomic data for the respondents and their households. The respondents were asked to describe their characteristics via the following constructs: gender, age, household income range, education, occupation, number of worker in household, number of vehicle in the household, vehicle type most used by the respondent, vehicle age, and workplace postal code.

Recent trip

This section focused on the respondent's most recent trip on I-495. The purpose of this section was to use respondent's experienced trip condition as a pivot point when designing the SP questions. This ensured that the stated scenario in the SP part was realistic for each respondent. The respondent was asked to describe his/her most recent trip information on I-495 via the following constructs: number of passenger, trip purpose, departure time, arrival time, preferred departure time, preferred arrival time, total travel time in minutes, total trip distance in miles, fuel cost, parking cost, toll cost, entry and exit ramp locations, shortest and longest travel time experienced on the whole trip in minutes, shortest and longest travel time experienced on the beltway in minutes, number of departure time alternatives respondents have considered, corresponded departure and arrival time for the alternative departure time, work starting/ending time, and work schedule flexibility (whether he/she could start work 30 min later).

Stated preference questionnaire

Two SP experiments were including in the survey. The first experiment presented respondents with various lane choice

Table 3 Stated preference (SP) experiment 2 attributes and levels

Variable	Normal lane	High occupancy toll (HOT) lane	High occupancy vehicle (HOV) lane (passengers $\geq$2)
Departure time/min	DT$-$40	DT$-$40	DT$-$40
	DT$-$20	DT$-$20	DT$-$20
	DT	DT	DT
	DT+20	DT+20	DT+20
	DT+40	DT+40	DT+40
Total travel time range/min	*If DT in peak hour*		
	TT_{min}+20–TT_{min}+30	TT_{min}+10–TT_{min}+20	TT_{min}+10–TT_{min}+20
	TT_{min}+20–TT_{min}+40	TT_{min}+10–TT_{min}+25	TT_{min}+10–TT_{min}+25
	TT_{min}+20–TT_{max}	TT_{min}+10–TT_{min}+30	TT_{min}+10–TT_{min}+30
	TT_{min}+20–TT_{min}+45	TT_{min}+10–TT_{min}+25	TT_{min}+10–TT_{min}+25
	TT_{min}+20–TT_{min}+35	TT_{min}+10–TT_{min}+20	TT_{min}+10–TT_{min}+20
	If DT not in peak hour		
	TT_{min}+10–TT_{min}+20	TT_{min}+5–TT_{min}+10	TT_{min}+5–TT_{min}+10
	TT_{min}+10–TT_{min}+30	TT_{min}+5–TT_{min}+15	TT_{min}+5–TT_{min}+15
	TT_{min}+10–$TT_{max}$$-$10	TT_{min}+5–TT_{min}+20	TT_{min}+5–TT_{min}+20
	TT_{min}+10–$TT_{max}$$-$20	TT_{min}+5–TT_{min}+15	TT_{min}+5–TT_{min}+15
	TT_{min}+10–$TT_{max}$$-$30	TT_{min}+5–TT_{min}+10	TT_{min}+5–TT_{min}+10
Arrival time range	Calculation corresponded to the departure time and arrival time range		
Fuel cost/$	*If DT in peak hour*		
	FC(1+10%)	FC	FC
	FC(1+20%)	FC(1+10%)	FC(1+10%)
	FC(1+30%)	FC(1+20%)	FC(1+20%)
	If DT not in peak hour		
	FC(1+10%)	FC	FC
	FC(1+15%)	FC(1+15%)	FC(1+15%)
	FC(1+20%)	FC(1+20%)	FC(1+20%)
Toll/$	0	*If DT in peak hour*	0
		0·3 per mile × *D*	
		0·35 per mile × *D*	
		0·4 per mile × *D*	
		0·45 per mile × *D*	
		0·5 per mile × *D*	
		If DT not in peak hour	
		0·1 per mile × *D*	
		0·15 per mile × *D*	
		0·2 per mile × *D*	
		0·25 per mile × *D*	
		0·3 per mile × *D*	

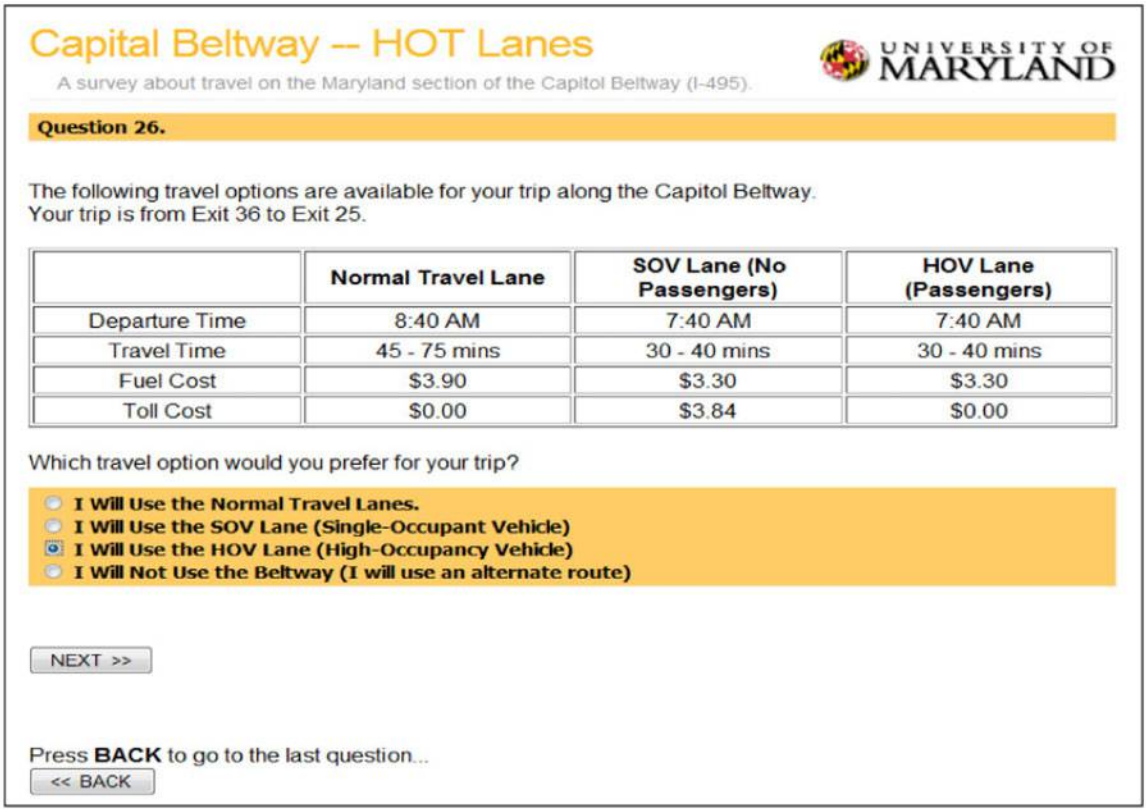
DT: departure time; D: difference in exit numbers for the trip; FC: fuel cost; TT_{min}=shortest travel time experienced on the whole trip in minutes; and TT_{max}: longest travel time experienced on the whole trip in minutes.

options under different travel time conditions (normal, congested, and uncertainty). The second experiment added departure time as an attribute and presented different lane and time options to respondents. The following sections describe the experimental design of these experiments.

Experiment 1: toll lane use and travel time variability

The first experiment (SP1) presented respondents with different travel conditions on three different lane alternatives to investigate the acceptability of toll lanes and the willingness to pay for reduced travel time subject to congestion and uncertainty. It is assumed that on the HOT lane, travel times will be significantly reduced due to less congestion and uncertainty. Seven scenarios were proposed to each respondent with differing levels of variation and were constructed based on the actual trip characteristics to ensure that alternatives are realistic. This experiment consisted of three alternatives (normal lane, managed lane (HOT), and managed lane (HOV)) and five variables. In addition to the three alternatives displayed, the respondent could choose to take an alternative route that does not include the Beltway. Each variable had up to three levels of variation per alternative. The survey was designed with an orthogonal design approach. The descriptions of the variables used in the experiment are as follows:

- Average travel time: This was the travel time the respondent can generally expect for their trip. This time was given for both the entire trip and the Beltway portion.
- Travel time due to congestion: This was the additional travel time the respondent could expect when congestion occurs. This time was given for both the entire trip and the Beltway portion.
- Travel time due to uncertainty: This was the additional travel time the respondent could experience for unlikely events such as accidents or sporting events. This time was given for both the entire trip and the Beltway portion.
- Fuel cost: This variable was designed to reflect varying fuel costs due to fuel economy difference and change in



2 Stated preference (SP) experiment 2: web interface

fuel price per unit. The fuel cost was pivoted from the reported fuel cost in the RP part.

- Toll cost: The toll cost was designed as a flat fee. This was one of the options under analysis at Maryland SHA.

The questionnaire design of the SP1 experiment is shown in Table 2 and Fig. 1 illustrates the presentation of this experiment on the website.

Experiment 2: departure time and uncertainty in travel time

This experiment consisted of three alternatives (normal lane, managed lane (HOT), and managed lane (HOV)) and five variables. Respondents were presented with seven scenarios. These variables had a maximum of five levels of variation per alternative. The variables included in the SP were: departure time, travel time range, arrival time range, fuel cost and toll. These variables were designed to account for traffic conditions by time of day, taking into account observed respondents' departure time where the peak period is defined as 8:00 AM–10:00 AM and 3:00 PM–7:00 PM. The descriptions of the variables used in the second experiment are as follows:

- Departure time: Departure time was pivoted from respondent's reported departure time.
- Total travel time range: This variable was designed to account for both time of day conditions based on the respondent reported departure time and travel condition on toll lane. It is aimed at capturing travel time uncertainty.
- Fuel cost: The fuel cost was designed to reflect higher expenses in the peak period and on the normal lane. The fuel cost is pivoted from the reported fuel cost in the RP part.
- Toll cost: The toll cost was designed to be mileage-based using the Inter-county Connector toll rates (Maryland Department of Transportation, 2010). The toll rate for the HOT lane accounts varied depending on whether the respondent's reported departure time is in the peak or non-peak period.

The questionnaire design of the SP2 experiment is shown in Table 3 and Fig. 2 provides an example of one of the scenarios proposed to the respondents on the website.

Descriptive statistics

A sample size of 173 completed surveys was collected. The respondent's characteristics are divided into two groups, socioeconomics and trip characteristics. The distribution of the sample is presented next.

Socioeconomics results

The main characteristics of the respondents in the sample can be summarized as follow:

- Gender: 51% of respondents were male.
- Age: The average age was 43 and median age was 45. The youngest respondent was 19 and the oldest was 82.
- Education: 49% were at a graduate or professional level, 34% had a bachelor's degree and 8% had some college education.
- Occupation: 46% worked for a private company, whereas 30% worked for the government. Only 1·2% was unemployed.

Table 4 Trip characteristics statistics

Category	Case	Respondents	Percentage*
Carpool	Carpool	30	17·30
	Non-Carpool	143	82·70
Travel time/min	0–15	50	28·9
	16–30	71	41·0
	31–45	25	14·5
	46–60	11	6·4
	Greater than 60	16	9·2
Departure time	Before 6 AM	4	2·4
	6AM–8AM	30	17·8
	8AM–10AM	55	32·5
	10AM–12PM	9	5·3
	12PM–2PM	8	4·7
	2PM–4PM	10	5·9
	4PM–7PM	54	32·0
	After 7PM	3	1·8
Distance traveled/mile	0–5	5	2·9
	5–10	20	11·6
	10–20	56	32·4
	20–40	71	41·0
	40–60	7	4·0
	Greater than 60	13	7·5
Fuel cost	0–2·5	41	23·70
	2·5–5	54	31·20
	5–10	51	29·50
	10–20	12	6·90
	20–40	6	3·50
	Greater than 40	9	5·20
Parking cost	0	147	85·00
	0–5	10	5·80
	5–10	9	5·20
	10–20	5	2·90
	Greater than 20	2	1·20
Toll cost	0	162	93·60
	0–5	5	2·90
	5–10	3	1·70
	Greater than 10	3	1·70
Minimum freeway travel time/min	0–10	79	45·70
	11–20	68	39·30
	21–30	19	11·00
	31–45	3	1·70
	Greater than 45	4	2·30
Maximum freeway travel time/min	0–15	15	8·70
	16–30	33	19·10
	31–45	40	23·10
	46–60	27	15·60
	61–90	23	13·30
	91–120	23	13·30
	Greater than 120	12	6·90

*Travelers who skipped an answer were excluded from these statistics.

- Income: 32% had income above $150 000. 24% had income between $100 000 and $149 999. Similarly, 24% had income between $50 000 and $99 999.
- Number of workers in the household: 2·3% of households had no workers in the household, 27% have one worker, and 54% of have two workers.
- Number of vehicle per household: 2% of households had no vehicles, 27% had one vehicle, and 54% had two vehicles.

These statistics are comparable to individuals living and working in areas near the Capital Beltway. This area of the Washington, D.C. metro area is well-educated and generally middle to upper-middle class. In 2011, the median income of Montgomery County (where mostly of our data was collected) was about $93 000; which implies that low income households were slightly underrepresented by our sample.

Trip characteristics results

Respondents were also asked about their trips, mainly focusing on the mode of transportation, number of passengers, different times and costs associated with the trip, distance traveled, and others. A summary of statistics relative to trip characteristic is presented in Table 4.

Table 5 Lane choice model experiment 1 (SP1) – model estimation results

		Estimates							
		Model 1		Model 2		Model 3		Model 4	
Variable/units	Spline #	Coeff.		Coeff.		Coeff.		Coeff.	
Alternative-specific constant (ASC): normal lane		0·000		0·000		0·000		0·00	
ASC: managed lane SOV		−0·061	*	−1·646	*	−1·074	*	−0·777	*
ASC: managed lane high occupancy vehicle (HOV)		−3·170	*	−5·267	*	−5·050	*	−7·897	*
ASC: other route		−2·060	*	−5·441	*	−4·056	*	−5·260	*
Cost/$		−0·346	*	−0·451	*	−0·516	*		
Cost spline/$	1							−46·506	*
	2							−2·730	*
	3							−1·438	*
	4							−0·771	*
	5							−0·771	*
	6							−0·771	*
	7							−0·095	**
	8							−0·095	**
Previous trip was with passengers (dummy)		2·250	*	2·546	*	2·871	*	3·725	**
Travel time for work trip/min: mean		−0·013	*	−2·897	*				
Travel time for work trip/min: SD				1·295	*				
Travel time for work trip spline/min	1					−0·944	*	−2·614	*
	2					−0·229	*	−0·157	*
	3					−0·104		−0·157	*
	4					−0·104	*	−0·157	*
	5					−0·020		−0·059	*
	6					0·026		0·029	
	7					0·107		0·029	
	8					0·107		0·029	
Travel time for non-work trip/min: mean		0·037	*	−2·185	*				
Travel time for non-work trip/min: SD				1·360	*				
Travel time for non-work trip spline/min	1					−5·755	*	−5·917	
	2					−5·755	*	−5·917	*
	3					−0·389	*	−5·917	*
	4					−0·118	*	−0·170	*
	5					−0·118	*	−0·170	*
	6					0·280	*	0·084	**
	7					0·280	*	0·209	**
	8					0·280	*	0·209	**
Travel time due to congestion/min: mean		−0·002		−4·523	*				
Travel time due to congestion/min: SD				1·822	*				
Travel time in congestion spline/min	1					−3·445	*	−0·197	*
	2					−0·112	*	−0·197	*
	3					−0·112	*	−0·197	*
	4					−0·112	*	0·033	**
	5					0·071		0·033	**
	6					0·071		0·033	**
	7					0·071		0·033	**
	8					0·350		4·188	
Travel time due to uncertainty: mean		−0·005		−10·708	*				
Travel time due to uncertainty/min				4·868	*				
Travel time due to uncertainty spline/min	1					−0·027	**	−8·492	*
	2					−0·027	**	−0·028	**
	3					−0·027	**	−0·028	**
	4					−0·027	**	−0·020	**
	5					−0·027	**	−0·017	**
	6					−0·027	**	−0·017	**
	7					0·033		−0·017	
	8					0·112		3·503	
Model statistics		Model 1		Model 2		Model 3		Model 4	
Null loglikelihood		−1252·14		−1252·14		−1252·14		−1252·14	
Constants loglikelihood		−1014·86		−1014·86		−1014·86		−1014·86	
Final loglikelihood		−910·90		−730·79		−688·53		−598·52	
Rho-squared		0·272		0·416		0·450		0·522	
Observations		903		903		903		903	
Individuals		–		129		129		129	
Number of draws		–		1250		1000		1000	

*Significant at 95%; **significant at 90%.

Table 6 Departure time experiment (SP2): model estimation results

		Estimates				
		Model 1	Model 2	Model 3	Model 4	Model 5
Variable/units	Spline #	Coeff.·	Coeff.	Coeff.	Coeff.	Coeff.
ASC: normal lane		0·000	0·000	0·000	0·00	0·00
ASC: managed lane SOV		−1·450 *	−1·686 *	−1·716 *	−1·950 *	−1·067 *
ASC: managed lane high occupancy vehicle (HOV)		−4·280 *	−4·555 *	−4·626 *	−6·951 *	−6·314 *
Cost/$		−0·099 *	−0·102 *	−0·111 *	*	*
Cost spline/$	1				−9·196 *	−13·078 *
	2				−2·915 *	−1·911 *
	3				−2·129 *	−1·911 *
	4				−0·377 *	−0·327 *
	5				−0·377 *	−0·327 *
	6				0·379 *	−0·157 *
	7				0·379 *	−0·157 *
	8				16·378 *	8·820 *
Earlier depart time (dummy)		−0·392 *	−0·317 **	−0·294 **	−0·663 *	−0·736 *
Later depart time: work trip (dummy)		−0·327 *	−0·377 **	−0·400 **	−0·619 **	−0·800 *
Later depart time: non-work trip (dummy)		−0·717 *	−1·023 *	−1·056 *	−1·562 *	−1·667 *
Previous trip with passengers (dummy)		2·910 *	3·146 *	3·182 *	4·188 *	3·825 *
Travel time: work trip/min, mean		−0·039 *	−3·516 *			
Travel time: work trip/min: SD			1·758 *			
Travel time: work trip spline/min	1			−0·321 *	−0·742 *	−0·217 *
	2			−0·321 *	−0·117 *	−0·217 *
	3			−0·090 *	−0·117 *	−0·073 **
	4			−0·090 *	−0·117 *	−0·073 **
	5			0·051 **	−0·117 *	−0·073 **
	6			0·070	0·113 *	−0·073 **
	7			0·070	0·113 *	−0·015
	8			0·070	0·113 *	−0·014
Travel time: non-work trip/min: mean		−0·063 *	−2·946 *			
Travel time: non-work trip/min: SD			2·564 *			
Travel time: non-work trip spline/min	1			−1·233 *	−8·969 *	−15·204 *
	2			−1·233 *	−3·089 *	−15·204 *
	3			−0·124 *	−0·222 *	−0·211 *
	4			−0·124 *	−0·222 *	−0·211 *
	5			−0·096 *	−0·079	−0·028
	6			0·116 *	0·111	−0·028
	7			0·116 *	0·111	−0·028
	8			0·116 *	0·111	−0·028
Travel time range (max–min)/min		−0·016 **	−0·006	−0·018 **	−0·027 *	
Travel time range spline/min	1					−0·128 *
	2					−0·051
	3					−0·051
	4					−0·051
	5					−0·051
	6					1·275 *
	7					12·674 *
	8					12·794 *
Model statistics		Model 1	Model 2	Model 3	Model 4	Model 5
Null loglikelihood		−909·27	−909·27	−909·27	−909·27	−909·27
Constants loglikelihood		−668·57	−668·57	−668·57	−668·57	−668·57
Final loglikelihood		581·32	−525·23	−513·78	−425·29	−399·17
Rho-squared		0·360	0·422	0·435	0·532	0·561
Observations (individuals)		827	827	827	827	827
Individuals		–	125	125	125	125
Number of draws		–	1000	1000	1000	1000

*Significant at 95%; **significant at 90%.

Models and results

This section presents results obtained from models' estimated on data extracted from the two SP experiments conducted. The SP1 models (Table 5) were estimated on 129 respondents who gave 903 responses and contains nine independent variables: three alternative specific constants (normal lane being the base), cost, dummy variable for having a passenger on board, travel time for commute trips and other purposes, and travel time due to

Table 7 Lane choice experiment (SP1): value of time

	Model 1 (constant)	Model 2	Model 3	Model 4
Value of time: work trips/$ per h				
25th Percentile	–	3·07	26·57	12·21
50th Percentile	2·250	7·34	12·05	12·21
75th Percentile	–	17·58	−3·03	−2·24
Value of time: non-work trips/$ per h				
25th Percentile	–	5·98	668·81	460·15
50th Percentile	−6·416	14·97	13·73	13·26
75th Percentile	–	37·47	−32·59	−6·56
Value of time in congestion/$ per h				
25th Percentile	–	0·42	12·96	15·29
50th Percentile	0·347	1·44	12·96	−2·58
75th Percentile	–	4·94	−8·30	−2·58
Value of time uncertainty/$ per h				
25th Percentile	–	0·00	3·16	2·18
50th Percentile	0·867	0·00	3·16	1·59
75th Percentile	–	0·08	3·16	1·28

Table 8 Departure time experiment (SP2): value of time

	Model 1 (constant)	Model 2	Model 3	Model 4	Model 5
Value of time: work trips/$ per h					
25th Percentile	–	5·36	172·76	18·69	39·83
50th Percentile	23·67	17·54	48·58	18·69	13·35
75th Percentile	–	57·46	−37·50	−17·97	13·35
Value of time: non-work trips/$ per h					
25th Percentile	–	5·50	663·58	491·73	2788·56
50th Percentile	38·18	31·03	66·85	35·35	38·64
75th Percentile	–	174·79	−62·27	−17·67	5·14
Value of time variability/range/$ per h					
25th Percentile	–	3·34	9·50	0·55	9·40
50th Percentile	9·70	3·34	9·50	4·27	9·40
75th Percentile	–	3·34	9·50	−4·24	−233·78

congestion and uncertainty. Four model specifications are proposed: multinomial logit (model 1); mixed logit model with random parameters on travel time components, all specified as lognormal (model 2), mixed logit with non-parametric random components for travel time coefficients, specified as B-spline (model 3), and mixed logit as in model 3 with cost also specified as non-parametric random variable (model 4). Multinomial logit is found to be unable to recover significant coefficients for congested travel time and uncertainty and produces a positive travel time coefficient for non-work trips. In the other model specifications, all parameters are significant and have the expected sign. Concerning the goodness-of-fit measures, model 4 provides the highest rho-squared value.

In terms of VOT calculations (Sillano and de Ortúzar, 2005; Daly *et al.*, 2012; McFadden and Train, 2000; Hensher and Greene, 2003), the median VOT for work trips was about $12 per h in the non-parametric model and about $7·50 per h in the parametric mixed logit; for non-work trips these values were respectively $13·50 per h and $15 per h.[3]

By analyzing the results obtained with the B-spline, it can be seen that while the cost parameter is negative for the entire sample population, some travel time components have positive signs, although these are close to zero and not significant for the work trip travel time. As expected, recovering values for congested time and uncertainty is quite difficult even when dedicated SP surveys are in place. Concerning congestion time, half of the sample has a negative and constant value while the others have a value of congested time close to zero, including some with very high and positive values. Recovering the tail of the B-spline distribution is a difficult task and more observations should be collected for those outliers to find out what are the motivations that produce these high and positive values.

It is sensible to conclude that the value for congested time was about $13 per h and very similar to the VOT; this finding is consistent with what was found by Bastin *et al.* (2010) in a different experimental context. Very low values for travel time uncertainty are estimated; those values are between $1·60 per h and $3·00 per h.

Models for the second experiment were estimated on 125 respondents and 827 responses. The final model specification includes two alternative specific constants (with normal lane normalized to zero), cost, a dummy variable for having a passenger on board, departing earlier and departing late for work trips and non-work trips, travel time for commute trips and other purposes, and

[3] The state of Maryland generally uses an approximate value of time of $16/h for project evaluation.

travel time due to uncertainty (given as a range). Model 4 with non-parametric specification for all time and cost components provides the best fit. This model is able to capture differences in value of time between work and non-work trips, which are respectively about $13 per h and $38 per h. More importantly, the variable uncertainty, captured as a range, is now about $9·50 per h. Earlier and later departure time coefficients are all negative and significant. Later departure time is perceived more negatively than earlier departure time, especially for non-work trips

Conclusion and future research directions

The federal highway administration (FHWA) has a policy for converting existing HOV lanes into HOT use and for any significant change in HOV operations. Currently, implementing a HOT concept requires a value pricing project that would have to be approved by FHWA. This study has proposed both data collection and modeling methodologies that can be adopted for managed lanes project evaluation. Data collection is based on SP methods combined with a web-based, adaptive, and self-administrated survey. Although the response rate was low, the data collected is of good quality and has been successfully used for modeling travel behavior on managed lanes.

The main findings of this study can be summarized as follows:

- Under the hypothetical condition of introducing managed lanes, respondents were able to make trade-offs amongst the available alternatives and the choice preferences provided were sufficient for model calibration. Stated preference methods allows for modeling travelers' behavior for non-existing project alternatives such as managed lanes on the Maryland side of the Capital Beltway.
- The experiment in which additional travel time due to congestion and uncertainty were given as attributes was not very successful in recovering those parameters (at least in the specification with constant parameter). In addition, tolls given at a fixed rate generated low VOTs and the model was unable to recover differences in value of time between work and non-work trips.
- The second experiments in which departure time was explicitly given to respondents and where uncertainty in travel time was given as a range successfully recovered disutility to depart earlier and later, VOT for work and non-work trips, and congested time.
- The use of mixed logit, with both parametric and non-parametric distributions, allowed the analyst to recover heterogeneity in random parameters and to estimate distributions in values of travel time that can be used for dynamic tolling strategies.
- Non-parametric B-spline models always outperformed parametric mixed logit with lognormal distributions and gave more credible values for all the travel time components. The problem of recovering the tails of the distributions still exists; to transfer this approach into practice more observations could be collected to study the behavior on the tails.

To conclude, the approach provided here is suitable for projects concerning the implementation of managed lanes. More case studies are however necessary to generalize the findings and before and after studies are also necessary to validate the results obtained with SP data.

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