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Authors
Lam, Terence C.
Small, Kenneth A.

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Terence C Lam
Kenneth A Small

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The value of time and reliability: measurement from a value pricing experiment

Terence C. Lam [a], Kenneth A. Small [b,*]

[a] *Department of Civil and Environmental Engineering, University of California, Davis, USA*
[b] *Professor of Economics, University of California, Irvine, CA 92697-5100, USA*

Abstract

We measure values of time and reliability from 1998 data on actual behavior of commuters on State Route 91 in Orange County, California, where they choose between a free and a variably tolled route. For each route at each time of day and for each day of the week, the distribution of travel times across different weeks is measured using loop detector data. The best-fitting models represent travel-time by its median, and unreliability by the difference between the 90th percentile and the median. We present models of route choice both alone and combined with other choices, namely time of day, car occupancy, and installation of an electronic transponder. In our best model, containing all these choices except time of day, value of time (VOT) is $22.87 per hour, while value of reliability is $15.12 per hour for men and $31.91 for women. These values are 72%, 48%, and 101%, respectively, of the average wage rate in our sample. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Recent policy innovations regarding highway congestion underscore the importance of knowing how travel-time and its reliability are valued by travelers. These innovations include experiments with congestion pricing and its cousin, value pricing,[1] as well as applications of information technology. All of them require, for their design and evaluation, knowledge of how

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[*] Corresponding author. Tel.: +1-949-824-5658, fax: +1-949-824-2182.
E-mail address: ksmall@uci.edu (K.A. Small).

[1] Here we use "value pricing" as defined by ITE Task Force (1998), namely to describe a policy that offers an optional superior service at a higher price. The "high occupancy/toll" lanes operating in Orange County (California), San Diego, and Houston are prominent examples. The term "value pricing" is sometimes used more broadly as a synonym for congestion pricing, notably in the US Value Pricing Demonstration Program.

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travelers will react to time-varying toll schedules and/or how they react to and evaluate changes in the extent and predictability of congestion.

Although the value of time (VOT) has been thoroughly studied, full consensus on many issues has not been achieved.[2] Furthermore, only a few empirical studies of VOT make use of information on road users' reactions to tolls, and even fewer do so with actual as opposed to hypothetical tolls. The value of reliability (VOR) has received much less attention.[3] Virtually all the work on it has used data related to hypothetical scenarios, for two reasons: measuring the variability of travel times facing actual travelers is difficult, and travel-time variability is highly correlated with mean travel time.

In this paper, we simultaneously measure VOT and VOR using data on actual travel behavior in a real pricing context. We observe people who face a choice between two parallel routes, one free but congested and the other with time-varying tolls. We do this by taking advantage of a nearly unique experiment in Orange County, California, on a major commuting highway known as State Route 91 (SR91).

In late 1995, a new privately constructed set of toll lanes in the center of SR91 (also known as the Riverside Freeway) opened, with tolls varying over time according to a preset schedule. This corridor connects fast-growing residential suburbs in Riverside and San Bernardino Counties to job centers in Orange and Los Angeles Counties. There are five free lanes and two toll lanes (called "express lanes") in each direction; we refer to the choice between them as "route choice" although in fact they are part of the same highway.

By summer 1998, when our data were collected, the toll had evolved to a highly sophisticated one; for example, people driving west (toward job centers in Orange and Los Angeles Counties) faced 12 different toll levels applying to different time periods, all identified on a published schedule. (This does not include the zero toll level, which continues to apply to the public lanes during all time periods.) Vehicles with three or more occupants are charged half the published toll. Our data come from mail surveys of people making work trips on the corridor for the entire 10-mile (16 km) length of the demonstration project (hence not using the few intermediate entrances and exits).[4]

There are two main difficulties with estimating VOT and VOR from such data. First, the main variables of interest – differences across the two routes in time, reliability, and cost – vary across times of day and days of the week, but in a highly correlated manner by design. Second, the survey responses must be supplemented by other data in order to accurately measure travel time and its uncertainty.

Kazimi et al. (2000) faced comparable difficulties with data from a value-pricing experiment in San Diego, and we follow a similar strategy. We overcome the second difficulty using data laboriously extracted from loop detectors placed by the California Department of Transportation (Caltrans) in both the free lanes and the express lanes. A serious limitation is that inability to

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[2] For recent reviews, see MVA Consultancy (1987), Small (1992, sect. 2.5), Waters (1996), Wardman (1998) and Mackie et al. (2001).

[3] See the reviews by Small et al. (1999) and Bates et al. (2001).

[4] At the time of our survey these intermediate entrances and exits were all low-volume roads. A few months after our data were collected, a major new toll road opened leading to job centers in Irvine and points south; it has an interchange with the segment of SR91 that contains value pricing, but only with the free lanes.

obtain satisfactory data for 1998 has forced us to use data from the same months in 1997, then apply an adjustment factor to account for growth in travel congestion in the free lanes between 1997 and 1998 Even so, these data are superior to either of the two most commonly used data sources on travel times in studies of actual behavior, namely survey-based estimates (which are subject to serious perception errors)[5] and network-based estimates (which usually cannot describe fine variation by time of day) Furthermore, we are able to measure the distribution of travel time across weeks, for a given 15 min time-of-day interval and a given day of the week, for up to 10 weeks during the summer months.

We overcome the first difficulty, that of correlation among variables, in several ways. First, by measuring travel times for relatively narrow (15 min) time-of-day intervals, we take advantage of substantial variation in the degree of congestion on the free route across the 4 h peak period (5–9 am), during which tolls on the express lanes are at a nearly constant level Second, the ratio of toll to travel-time savings is higher in the shoulders of the peak (4–5 am, 9–10 am) than in the peak itself, and higher still in the mid-day and night periods; by including work trips that occur during these off-peak periods, we obtain additional independent variation. Third, our measurements reveal that mean (or median) travel time and variability in travel time are only imperfectly correlated across time-of-day intervals, for example, variability is especially high late in the peak period. Fourth, carpooling introduces additional variation into the cost per person of the toll, both because the toll can be shared among occupants and because carpools of three or more receive a 50% discount Finally, one expects the VOT and VOR to depend on certain measurable socio-economic and travel characteristics, by specifying interactions between travel variables and these characteristics, we obtain additional independent variation in the variables entering the model

The result is that we have found many model specifications that fit well and result in statistically significant coefficients on all three of the key travel variables We thereby obtain credible estimates of VOT and VOR which vary in plausible ways with traveler characteristics

In Section 2, we describe our data more fully Subsequent sections report the results of various models that include route choice, first by itself and then simultaneously with related decisions – namely time of day, car occupancy, and installation of an electronic transponder (which is required to use the toll route) As it turns out, our estimates of VOT and VOR are fairly robust across different assumptions about the simultaneity of such decisions, with the exception of time of day which we are not able to treat very satisfactorily.

2. Data

Our mail survey is a modified version of one carried out a year earlier in the same corridor and analyzed by Parkany (1999)[6] Our sample consists of 162 from the 1997 survey plus 371 newly

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[5] See Small (1992, p. 17) for the effect of such errors on travel demand models There is evidence from both the Orange County and the San Diego experiments that people using the express lanes greatly overestimate the time differences between the express lanes and the free lanes, see Sullivan (1998, p 28) and Supernak et al (1999, p 31)

[6] The 1997 sample was designed and administered by Emily Parkany, in collaboration with David R Anderson and Kenneth Small

recruited by observing license plates on SR91 and getting the owners' addresses from the Department of Motor Vehicles.

The survey asked people in considerable detail about their most recent weekday work trip. The answers to these questions form the basis for most of our variables. In some cases we also use less detailed answers from a one-week trip diary, which enables us to perform cross-checks or imputations for certain questions. For example, many respondents neglected to tell us the car occupancy for their most recent trip, so for car occupancy we use instead (for all respondents) the average occupancy for the comparable work trips in the trip diary.

Our loop-detector data record traffic volume and vehicle density on each lane at every 30 s. From this information, we use a standard engineering algorithm (May, 1990, p. 199) to estimate the average travel times on both the free lanes and the tolled lanes, for either 5 or 15 min time-of-day intervals; we use the 15 min intervals in the models we report here because those data show ample systematic variation but fewer random fluctuations.

As noted earlier, the loop data were from one year prior to the survey. Because congestion has grown in the intervening year, such data understate the time differences that apply to the choices we observe, and therefore we overestimate the coefficients on the travel-time and reliability variables. In order to correct for this bias, we obtained some loop detector data also for 1998. The 1998 data are insufficient to create the detailed travel-time and reliability measures we need, but they do allow us to measure the extent of the general trend toward increasing congestion in the free lanes. Averaging over the 4 h peak period, we find that the median time difference between the two lanes is 37% larger in summer 1998 than in summer 1997.[7] We assume that the same growth factor applies to the entire distribution of travel-time differences and hence to our measures of reliability (described below). We therefore apply this growth factor when calculating VOT or VOR from our models: that is, we divide the coefficients of travel-time and of reliability by 1.37. This is equivalent to correcting all the travel-time and reliability data by this factor before estimating the model.

This factor seems large for a one-year change, but that is because the travel-time difference starts from a small base, growing from 4.3 min in 1997 to 5.9 min in 1998.[8] In 1997 the toll lanes were less than 2 years old, and arguably traffic levels in the corridor were still equilibrating after the huge initial improvement resulting from the 50% increase in capacity. Demand for peak travel that was latent before December 1995 probably was gradually becoming manifested as actual traffic. Residential development in the road's catchment area was very strong, and some anticipatory development may have been attracted by the imminent opening of another toll road, the

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[7] These calculations are available from the authors upon request. The median travel time for each 15 min interval is measured from observations over various weekdays for several weeks. For the free lanes we have data only for the three fastest lanes in 1998, so we recomputed the 1997 data for those same lanes. For the toll lanes, we assumed for both years a constant travel time of 9.17 min (65.4 miles per hour), which is what was measured in 1997 and did not change appreciably in 1998.

[8] Data for all four lanes, rather than the inner three, show an average travel-time difference of 5.6 min in 1997. Sullivan (1998, p. 28, Figs. 2–13) finds an average time savings over the same 4 h peak period was about 8 min in June 1997, also based on loop detector data. The remaining difference between our results and Sullivan's could be caused by differences in the many assumptions required to convert loop detector data into speeds estimates; see Sullivan (1998, pp. 48–50) and Lam (2000, Appendix C).

Table 1
Choice-based sampling weights

	Population share[a]	Sample share	Weight
Route choice			
Toll lanes	0 283	0 417	0 68
Free lanes	0 717	0 583	1 23
Mode choice			
HOV2+	0 221	0.256	0 86
Drive alone	0 779	0 744	1 05
Transponder choice			
Transponder	0 489	0 615	0 81
No transponder	0 511	0.385	1 33

[a] Measured by field observation counting cars in each set of lanes, with or without passengers, and with or without transponders (which are visible on the windshield)

Eastern Toll Corridor (SR-241 and SR-261), which provides a new route to some of the employment centers served by SR91 Still, we acknowledge that the small magnitude of the time savings involved makes our results vulnerable to measurement error

For budgetary reasons, we oversampled express-lane users, carpoolers, and people with transponders. relative to their frequency in the population Because these are choice categories in our models, such choice-based sampling biases the estimated coefficients, primarily the alternative-specific constants Mostly, we ignore this bias because we are not interested in those constants In some cases, we also performed estimations using weighted observations as in Manskti and Lerman (1977), and found indeed that only the alternative-specific constants were noticeably affected The sampling weights are shown in Table 1

3. Route choice only

In this section, we consider route choice to be conditional on time of day and car occupancy The model is a reduced form with respect to transponder choice – that is, we treat the decision to obtain a transponder and to set up a financial account simply as a necessary part of choosing the toll route, so that the associated disadvantages are reflected in the alternative-specific constant for the toll route

We assume that traveler n chooses route i ($i = 1, 2$) by maximizing the following conditional indirect utility function

$$U_{in} = V_i(t_{in}, v_{in}, c_{in}, x_n) + \varepsilon_{in},$$

where t, v, and c are the measures of travel time, variability in travel time, and cost, respectively (just a single measure of each in a given specification); x is a vector of observable socio-economic or other characteristics (including time of day and car occupancy), assumed exogenous, and ϵ is a random utility component whose distribution is extreme value (i e., double-exponential). These assumptions lead to a binomial logit model of choice of route The values of time and reliability are then defined as.

Table 2
Definitions of explanatory variables route choice

Variable	Description
Variables varying by route	
lane	Alternative-specific dummy for toll lanes
t	Travel time for 10 mile study section, by route and 15 min time-of-day interval for each weekday Distributions of t are measured across weeks of loop detector data in summer 1997
mean t	Mean travel time (min)
medt	Median travel time (min)
S D	Standard deviation of travel time (min)
dmp90	90th percentile of travel time minus median travel time (min)
cost	Cost of toll per person ($)
Variables varying only by individual	
y	Annual household income (in $000s), calculated as the mid-point of the income interval (or as 100 for the interval 95+)
$\bar{w}$	Proxy for wage rate (Annual gross household income)/2000 h
edu4	Dummy for college graduate or higher
dist	Total trip distance (miles)
flex	Flexibility of work arrival time in minutes, taken as the mid-point of the interval in Question 7 of the survey (or 120 if can arrive any time)
prof	Dummy for professional (doctor, lawyer, etc)
age	Age of the respondents (years)
lang	1 if another language besides English is spoken at home 0 otherwise
Male	Dummy for male
swrc	1 if respondent has ever switched to a route other than SR91 in the past two weeks, due to radio traffic reports
swtm	1 if respondent has ever switched to another time of day in the past two weeks, due to radio traffic reports

$$\mathrm{VOT}_n = (\partial V/\partial t_n)/(\partial V/\partial c_n),$$

$$\mathrm{VOR}_n = (\partial V/\partial v_n)/(\partial V/\partial c_n)$$

These quantities could in principle depend on route i, but in our specifications they do not so we omit the i subscript. In general, these quantities could depend on both x and the travel variables themselves, but in our specifications they depend only on x; in most cases they are simple linear combinations of estimated coefficients and x values

As the SR91 express lanes have virtually no congestion, all the travel-time differences in our data represent congested time Therefore, so does our estimated VOT The value of uncongested time would be lower, according to previous research such as described by Calfee and Winston (1998) and Small et al. (1999)

Table 2 defines the specific variables we use Table 3 shows how the differences in these variables across the two routes are correlated with each other in our sample

Table 4 shows the results of four sparse model specifications that perform well All use unweighted observations, so the alternative-specific coefficient (that of the variable *lane*) is biased. The first two specifications differ by whether travel time is measured as mean or median, and by whether variability is measured as standard deviation (denoted S D.) or the difference between the

Table 3
Correlation among time, reliability, and cost differences between routes[a]

	mean t	medt	S.D.	dmp90	cost	$c/\bar{w}$
mean t	1					
medt	0.913	1				
S.D.	0.659	0.329	1			
dmp90	0.448	0.115	0.891	1		
cost	0.597	0.495	0.474	0.369	1	
cost/w	0.172	0.171	0.084	0.065	0.210	1

[a] Number of observations 389.

Table 4
Unweighted logit estimation of route choice (asymptotic t-statistics in parentheses)

Variable	(1a)	(1b)	(1c)	(1d)
lane	0.054 (−0.122)	−0.176 (−0.411)	−1.630*** (−2.914)	−0.367 (−0.841)
y*lane	–	–	0.0189*** (4.133)	–
mean t	−0.068 (−0.749)	–	–	–
medt	–	−0.133* (−1.926)	−0.160** (−2.151)	–
medt*$w^{1/2}$	–	–	–	−0.0233** (−1.991)
S.D.	−0.268*** (−2.828)	–	–	–
dmp90	–	−0.228*** (−4.279)	−0.222*** (−2.151)	–
dmp90*$w^{1/2}$	–	–	–	−0.034*** (−3.607)
cost	−0.433*** (−3.515)	−0.471*** (−3.743)	−0.428*** (−3.185)	–
cost/$\bar{w}^{1/2}$	–	–	–	−1.711*** (−3.230)
N	389	389	351	351
Log likelihood	−252.740	−250.304	−219.335	−219.922
Pseudo R^{2a}	0.0627	0.0717	0.0985	0.0961
VOT($/h)[b]	–	–	16.37	0.596w
VOR($/h)[b]	27.11	21.20	22.72	0.870w
VOR/VOT	–	–	1.39	1.46

* Coefficient is significant at 10% level.

** Coefficient is significant at 5% level.

*** Coefficient is significant at 1% level.

[a] *Note*. Pseudo R^2 is $1 - L/L_0$, where L is the log-likelihood value at the estimated parameters and L_0 is the log-likelihood value for a model with alternative-specific dummies only.

[b] In calculating VOT and VOR, the coefficients of travel-time and travel-time variability are divided by 1.37 to account for understatement of time differences in variable t; see text. Not reported unless the relevant coefficients are both statistically significant at 5% level.

90th and 50th percentile values (denoted *dmp90*), this latter measure follows Kazimi et al. (2000). We find that in terms of log-likelihood achieved, *dmp90* explains choices substantially better than S.D., and median travel time performs slightly better than mean travel time. These findings may result from inaccuracies in computing statistical moments such as mean or S.D. from small samples, but they may also indicate that the median and 90th percentile of the distribution of travel time are good proxies for what people actually care about.

We also tried various ways of interacting household income Y or individual wage rate w with the travel variables, in order to allow VOT, VOR, and/or the alternative-specific constant to vary with these characteristics. This proved to be important because the coefficient of travel time is insignificant, or only marginally significant, when income is not somehow included. Model (1c) allows Y (entered as $y = Y/1000$) simply to increase the probability of choosing the toll lane, whereas in model (1d) VOT and VOR are assumed proportional to Y (entered for convenience in the form $\bar{w} \equiv Y/2000$, a crude proxy for wage rate). In addition to the models shown, we tried multiplying median time by wage rate or dividing cost by wage rate – thereby forcing VOT and VOR to be proportional to either w or $\bar{w}$, just as in model (1d). We also used reported wage rate w rather than the crude proxy $\bar{w}$, getting similar results, but doing so causes a loss of observations because many respondents did not answer that question. The best-fitting model is the simple one shown as (1c), in which VOT and VOR are constants and the alternative-specific constant is replaced by a linear function of household income.

The implied VOT and VOR for these models are shown at the bottom of the table. They are adjusted for understatement of the time and reliability differences, as described earlier. In the two models including income, which we regard as more reliable, the VOT is \$16.37/h and 59.6% of $\bar{w}$, respectively, well within the range of previous estimates of value of congested travel-time. (By way of comparison, the weighted mean of the actual wage rates reported in our sample is \$31.69/h,[9] hence the estimate in model (1c) is 52% of the wage rate.)

It is often claimed that people are more concerned with travel time reliability than with travel time itself. The measures used in Table 4 are all in the same units, namely minutes, so such a comparison has precise meaning. For these measures, this expectation is confirmed, with VOR 39–46% higher than VOT in models (1c) and (1d).

Table 5 reports more elaborate specifications, which generalize model (1c) by adding measures of education, age, native language, work-hour flexibility, occupation, trip distance, gender, and two measures of people's propensity to vary their commute from day to day. Most of these characteristics are interacted with the alternative-specific dummy (*lane*), but a few are interacted instead with travel time or its variability. These models suggest that choosing the toll route is favored by high household income, speaking English at home, and lack of options to switch to routes other than SR91. (We give less credence to this last variable, *swrc*, because it may be endogenous, indicating that those unwilling to pay the toll are more likely to seek out other routes to save time.) Women are substantially more averse to travel-time variability than men, alternatively, if gender is instead interacted with the alternative-specific constant – not shown in the

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[9] It is computed as a weighted average, using the weights in the first panel of Table 1, of our sample mean wages for toll lane users and regular lane users.

Table 5
Unweighted and weighted logit estimation of route choice (asymptotic t-statistics in parentheses)

Independent variable	Unweighted			Weighted
	(1e)	(1f)	(1g)	(1h)
lane	−2.523**	−1.193	−2.811***	−3.514***
	(−2.200)	(−1.413)	(−2.884)	(−3.372)
y*lane	0.0202**	0.0202**	0.0197***	0.0189***
	(3.681)	(3.696)	(3.905)	(3.569)
edu4*lane	−0.519*	−0.522*	–	–
	(−1.775)	(−1.786)		
age*lane	−0.0122	−0.0119	–	–
	(−0.899)	(−0.877)		
lang*lane	−1.149***	−1.164***	−1.129***	−1.115**
	(−2.591)	(−2.611)	(−2.737)	(−2.393)
flex*lane	0.00535*	0.00533*	0.00518**	0.00537**
	(1.947)	(1.934)	(1.958)	(1.996)
prof*lane	0.989*	0.973*	–	–
	(1.808)	(1.801)		
dist*lane	0.0621**	–	0.0481*	0.0498
	(2.010)		(1.700)	(1.614)
dist^2*lane	−0.000611**	–	−0.000476*	−0.000474
	(−1.994)		(−1.721)	(−1.560)
swrc*lane	−0.851***	−0.862***	–	–
	(−2.581)	(−2.607)		
swtm*lane	0.682*	0.735*		
	(1.716)	(1.837)		
medt	−0.182**	0.111	−0.176**	−0.180**
	(−2.205)	(.715)	(−2.208)	(−2.150)
dist*medt	–	−0.0138**	–	–
		(−2.188)		
dist^2*medt	–	0.000141**	–	–
		(2.156)		
dmp90	−0.261***	−0.255***	−0.263***	−0.271***
	(−3.802)	(−3.710)	(−3.983)	(−4.068)
male*dmp90	0.155**	0.151**	0.154***	0.159***
	(2.542)	(2.476)	(2.631)	(2.677)
cost	−0.388***	−0.377**	−0.401***	−0.391***
	(−2.617)	(−2.553)	(−2.790)	(−2.682)
N	339	339	341	341
Log likelihood	−195.680	−195.375	−203.902	−185.454^{a}
Pseudo R^2	0.1672	0.1685	0.1373	0.1549

[a] Not comparable to other log likelihood values because observations are weighted. See notes to Table 4.

table – women are more likely than men to choose the toll route. The coefficient on higher education has an unexpected sign, but is insignificant at a 5% level.

One might expect that greater work-hour flexibility (*flex*) would make travel-time variability less onerous, and so favor choice of the free route. Yet if anything the opposite seems to be the case, with *flex*lane* showing a positive effect or alternatively, in a model not shown, *flex*dmp90* showing a negative effect (in both cases falling just short of significance at a 5% level). A possible

Table 6
Implied values of travel-time and reliability (asymptotic *t*-statistics in parentheses)

Trip distance in miles (%)	Value of time ($/h)[a]			
	(1e)	(1f)	(1g)	(1h)
13 (5%)		5.18		
27 (25%)		18.45		
37 (50%)		24.00		
40 (mean)	20.54	25.02	19.22	20.16
50 (75%)		26.31		
74 (95%)		16.04		
92 (99%)		−4.05		
	Value of reliability ($/h)[a]			
Male	11.96	12.08	11.90	12.55
Female	29.46	29.62	28.72	30.35

[a] Adjusted for understatement of time differences, see text and note to Table 4.

explanation is that people with flexible work hours have more opportunity to advance their careers by spending time at the office and/or being punctual when they have appointments, and therefore value time and reliability more highly. Or it may be that flexibility is serving as a proxy for occupations with higher wage rates, showing up because wage is only imperfectly reflected in our specifications.

Model (1f) suggests that VOT may be quadratic in total trip distance, peaking at about 49 miles and becoming negative for trips longer than 98 miles. Although this model fits slightly better, model (1e) has a simpler and more plausible structure for VOT. Model (1g) is the same as (1e) except it omits the statistically insignificant interactions with *lane* and also omits *swrc* due to its likely endogeneity. Model (1g) is the basis for our specifications of joint choices in the sections that follow. All the coefficients are quite robust across those specifications in which they have comparable meanings, an exception is distance, whose effects on the alternative-specific constant become somewhat smaller when other variables are omitted.

Model (1h) is just (1g) re-estimated using sampling weights, as explained earlier. As already noted, coefficients other than the alternative-specific constants are barely affected by weights. For this reason, we show only unweighted models in what follows.

Table 6 displays the values of VOT and VOR implied by models (1e)–(1h), again adjusting for understatement of travel-time and reliability differences. In our best model, (1g), VOT is $19.22/h, which is 61% of the mean wage, VOR is lower than VOT for men and higher than VOT for women.

4. Route and time-of day choice

We now turn to models that relax the assumption of an exogenous time of day for the work trip. This assumption could bias the results in Section 3, if unobserved factors affecting route choice are correlated with those affecting time-of-day choice. This is because time of day is the primary determinant of the value of our independent variables describing time, reliability, and cost. In particular, if travelers who pay the toll are as a result more likely to choose to travel in the busiest part of the rush hour, our method of computing time and reliability variables will assign them a larger than average travel-time saving and reliability improvement from taking the toll lane. This will create a spurious correlation between the route chosen and the time and reliability differences, effectively attributing too much of their choice to these variables and not enough to random factors This will cause an upward bias in the measured VOT and VOR.

We follow the strategy of Small (1982) by assuming that the key factor in time-of-day choice is arrival time at the workplace. We define twelve 30 min time-of-day intervals for work arrival, ranging from 4.00–10.00 am We asked each traveler the actual arrival time for the most recent weekday trip; we then infer from other information about their trip what the arrival time would have been given each of the other possible route and time-of-day choices The traveler is then assumed to incur a disutility for arrival at any time other than the official work start time For late arrivals, this disutility includes a fixed penalty for any late arrival, plus a further penalty per minute late For early arrivals, the disutility is simply per minute early We also specify a set of alternative-specific dummy variables for 11 of the 12 times of day; these can account for non-work-related factors affecting the convenience of different times of day All these variables are described in Table 7.

Our main limitation is not knowing the travel times and reliabilities for parts of the trip other than on the 10-mile study corridor Those times and reliabilities played no role in the route-choice models of Section 3, but they matter here because they vary across the time-of-day alternatives We tried two alternative proxies for these variables For the first, we simply ignore the rest of the trip and use the same variables as before (*medt* and *dmp90*). This forces the alternative-specific constants to account for any differences across times of day in congestion encountered on the rest of the trip, and so does not fully eliminate the biases described earlier. For the second proxy, we assume that the 50th and 90th percentile travel times on the rest of the trip are equal to the 50th and 90th percentile travel times on the free lanes on our 10 mile study corridor, inflated by distance except excluding a 5 mile access portion that is assumed uncongested We call these variables *medtinf* and *dmp90inf*, using “inf” for “inflated”

Table 8 shows the results of four models, the first two using the first proxy just described and the others using the second proxy Models (2b) and (2d) follow the specification of model (1g) for those variables related directly to route choice. and assume that scheduling disutility depends on gender, age, and work-hour flexibility For convenience, the sample average has been subtracted from *age* to facilitate calculation of marginal rates of substitution – so, for example, model (2d) implies that a 41-year-old male would tolerate an extra $(-0\,0285+0\,0126)/(-0\,0463)=0.343$ min of congested travel in order not to have to arrive one additional minute earlier than the desired work arrival time

In models (2a)–(2b), the travel-time variable *medt* is insignificant, suggesting this variable is a poor proxy for the full-trip travel times that would be encountered at different times of day Model (2d) fits best when all four are re-estimated on a common sample, and it is significantly better than (2c) based on a likelihood-ratio test with eight degrees of freedom [10] The coefficients of the

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[10] The values of log likelihood for models (2a) and (2c) with sample size of 341 are −781 245 and −776 019, their differences with those of models (2b) and (2d) reject the null hypotheses that all eight additional coefficients of socio-economic factors are zero

Table 7
Definitions of additional explanatory variables for other choices

Variable	Description
Variables that vary by time of day	
D*n*	Alternative-specific dummy for work arrival during time interval $(n - 0.5)$ to n h past midnight, $n = 5, \ldots, 10$
D*n*h	Alternative-specific dummy for work arrival during time interval n to $(n + 0.5)$ h past midnight $n = 5, \ldots, 9$
Te	(Official work start time) − (lower limit of time-of-day alternative)
Dlate	Lateness dummy 1 if $Te < 0$, 0 otherwise
SDE	Schedule delay early $\mathrm{Max}\{Te, 0\}$
SDL	Schedule delay late $\mathrm{Max}\{-Te, 0\}$
medtinf	Estimated time for full trip calculated as ((dist-5)/10)$*$medt$_f$ for free lanes, ((dist-15)/10)$*$medt$_f$ + medt$_t$ for toll lanes, where medt$_f$ & medt$_f$ are the median travel time on free & tolled lanes on the 10 mile study section
dmp90inf	Estimated variability for full trip same as medtinf except substitute dmp90 for medt throughout
Variables that vary by mode or transponder choice	
SOV	Alternative-specific dummy for drive alone
HOV2	Alternative-specific dummy for carpool with one other person
HOV3	Alternative-specific dummy for carpool with two more other people
TAG	Alternative-specific dummy for obtain transponder
Variables that vary only by individual	
edu0	Dummy for high school graduate or lower
cars	Number of cars shared by household
pool	Travels by carpol (HOV2 or HOV3)

time-of-day dummies suggest that respondents have an inverted U-shape utility curve with regard to travel at different times of day, which reaches a maximum at work arrival around 7:30–8:00 am.

The marginal rate of substitution between SDL and SDE is around 1.7 for a 41-year-old female with inflexible work hours; it varies by gender, age, and employer's policy toward work-hour flexibility. Furthermore, the discrete penalty for any late arrival is quite large, equal in model (2d) to $(-1.0784)/(-0.428) = \$2.52$. These results are generally consistent with earlier studies of scheduling choice. Some other implied marginal rates of substitution are shown in Table 9.

Models (2b) and (2d) show that males and older workers are more likely to arrive early for work, all else equal. One plausible explanation is that such workers have fewer family obligations. In Model (2d), the difference between men's and women's disutilities of travel-time variability is both small and statistically insignificant, in contrast to model (1g), this suggests that the difference observed earlier was partly due to scheduling preferences, which were inadequately accounted for in the route-choice-only models.

We also estimated some of these specifications as nested-logit models, using maximum likelihood. When the upper-level branch was defined by time of day, the coefficient of inclusive value was imprecisely estimated at around 2.0. A model with the upper-level branch defined by route achieved a higher likelihood value, but the coefficient of inclusive value was over 7.0. Both of these values are outside the acceptable interval [0,1]. Fortunately, the parameters of interest were hardly affected at all by these variations.

Table 8
Joint estimation of route and time-of-day choice (asymptotic *t*-statistics in parentheses)

Independent Variable	(2a)	(2b)	(2c)	(2d)
D5	0.784	0.811	0.793	0.815
	(0.678)	(0.702)	(0.686)	(0.706)
D5h	1.968*	2.0388*	2.244**	2.312**
	(1.871)	(1.936)	(2.122)	(2.185)
D6	2.409**	2.533**	2.907***	3.0343***
	(2.310)	(2.426)	(2.740)	(2.858)
D6h	2.559**	2.748***	3.331***	3.507***
	(2.440)	(2.606)	(3.052)	(3.197)
D7	3.298***	3.449***	4.314***	4.470***
	(3.152)	(3.266)	(3.880)	(3.985)
D7h	3.668***	3.857***	4.608***	4.782***
	(3.494)	(3.631)	(4.143)	(4.251)
D8	3.917***	4.0748***	5.193***	5.395***
	(3.706)	(3.806)	(4.543)	(4.658)
D8h	3.347***	3.462***	4.925***	5.182***
	(3.141)	(3.204)	(4.164)	(4.311)
D9	3.889***	3.952***	4.833***	5.00597***
	(3.711)	(3.720)	(4.378)	(4.464)
D9h	3.700***	3.773***	4.377***	4.494***
	(3.549)	(3.570)	(4.093)	(4.142)
D10	2.943***	3.0936***	3.258***	3.432***
	(2.782)	(2.888)	(3.064)	(3.186)
Lane	−0.869*	−2.105**	−0.476	−1.563*
	(−1.732)	(−2.403)	(−1.155)	(−1.907)
*y**lane	0.0174***	0.0175***	0.0174***	0.0172***
	(3.933)	(3.662)	(3.955)	(3.630)
lang*lane	–	−0.981**	–	−1.00542**
		(−2.443)		(−2.535)
flex*lane	–	0.00525**	–	0.00456*
		(2.065)		(1.831)
dist*lane	–	0.0546**	–	0.0548**
		(1.970)		(1.984)
dist^2*lane	–	−0.000588**	–	−0.000605**
		(−2.126)		(−2.192)
medt[a]	−0.101	−0.115	–	–
	(−1.392)	(−1.541)		
medtinf	–	–	−0.0492**	−0.0463**
			(−2.208)	(−2.059)
dmp90[a]	−0.115**	−0.153**	–	–
	(−2.109)	(−2.496)		
male*dmp90	–	0.0941*	–	–
		(1.812)		
dmp90inf	–	–	−0.0571***	−0.0725***
			(−3.026)	(−2.959)
male*dmp90inf	–	–	–	0.0166
				(.821)

Table 8 (Continued)

Independent Variable	(2a)	(2b)	(2c)	(2d)
cost	−0.442***	−0.441***	−0.404***	−0.428***
	(−3.377)	(−3.181)	(−3.239)	(−3.236)
Dlate	−1.196***	−1.0618**	−1.209***	−1.0784**
	(−2.642)	(−2.319)	(−2.667)	(−2.341)
SDE	−0.0216***	−0.0284***	−0.0216***	−0.0285***
	(−8.265)	(−7.406)	(−8.186)	(−7.213)
male*SDE	–	0.0123***	–	0.0126***
		(2.717)		(2.633)
(age-41)*SDE	–	0.000550**	–	0.000542**
		(2.374)		(2.345)
SDL	−0.0372***	−0.0470***	−0.0372***	−0.0465***
	(−4.035)	(−4.046)	(−4.025)	(−3.988)
flex*SDL	–	0.000179**	–	0.000170*
		(2.085)		(1.965)
N	349	341	349	341
Log likelihood	−801.765	−763.729	−796.871	−760.0746
Pseudo R^2	0.2771	0.2953	0.2815	0.2986
VOT(\$/h)^{b}	10.01	11.42	5.33	4.74
VOR(\$/h)^{b}				
Male	11.39	5.85^{c}	6.19	5.72^{c}
Female	11.39	15.19^{c}	6.19	7.42^{c}

[a] Calculated for 30 min time-of-day intervals rather than 15 min as in Tables 3–5

[b] Adjusted for understatement of time differences. see text and note to Table 4 Not reported unless the relevant coefficients are both statistically significant at 5% level

[c] Male–female difference not significant at 5% level in this model

Implied values of time and reliability (VOT and VOR) are shown in the last four rows of Table 8 Like those in earlier tables, they are adjusted for understated travel times, since all the time and reliability differences in the variables entering these models are ultimately based on the 1997 measurements of median and 90th-percentile travel times VOT and VOR in these models are much smaller than those of the route-choice-only models We suspect there are two reasons for the difference First, the upward bias in estimated VOT and VOR from route choice only, discussed earlier, may be quite large. Second, our proxies for the time and reliability encountered during the parts of the trip outside the range of our loop-detector data are undoubtedly inaccurate, perhaps the resulting errors-in-variables bias causes VOT and VOR to be seriously underestimated here. Unfortunately, we do not know of a way to assess which of these factors is operating more strongly

5. Route and mode choice

In this section, we return to the assumption of exogenous time of day but relax a different assumption, namely that carpooling is exogenous We assume the traveler chooses among three possible modes: solo driver (SOV), carpool with one other person (HOV2), and carpool with two

Table 9
Implied per-minute cost of schedule delay early/late (asymptotic t-statistics in parentheses)

Age (%)	Marginal rate of substitution between SDE and travel time[a]					
	(2a)	(2b)		(2c)	(2d)	
		Male	Female		Male	Female
21 (1%)		0.3228	0.4694		0.7912	1.164
29 (10%)		0.2704	0.4170		0.6629	1.036
41 (50%)	0.2930	0.1918	0.3383	0.6014	0.4705	0.8433
55 (90%)		0.1001	0.2466		0.2459	0.6188
70 (99%)		0.0018	0.1483		0.0054	0.3782

Flexibility	Marginal rate of substitution between SDL and travel time[a]			
	(2a)	(2b)	(2c)	(2d)
0		0.5599		1.376
15		0.5279		1.300
30		0.4959		1.225
45		0.4640		1.150
60	0.5046	0.4320	1.036	1.074
75		0.4000		0.9987
90		0.3680		0.9232
105		0.3360		0.8477
120		0.3040		0.7723

[a] Adjusted for understatement of time differences, see text and note to Table 4. In this case, the values are multiplied instead of divided by 1.37, because the coefficient of travel-time appears in the denominator instead of the numerator of the ratios of coefficients.

or more other people (HOV3). Recall that the toll for HOV3 vehicles is half the toll for other vehicles, even before dividing the cost among the occupants.

Table 10 first shows a model of mode choice alone, explained just by household characteristics. It is not conditional on route choice, but rather is a reduced form. It suggests that long trip distance, foreign language, and large workplace are especially conducive to HOV3, while low levels of car ownership and low levels of education favor HOV2.

Models (3b) and (3c) are joint models of carpooling and route choice. Each has six alternatives, consisting of two possible routes for each of the three possible modes. Model (3b) is logit, while (3c) is nested logit with mode the upper choice level and route the lower level. Model (3c) has an implausible sign for the coefficient of inclusive value and does not fit significantly better under a likelihood-ratio test, suggesting that joint logit as in (3b) is an adequate description. All the other coefficients have plausible signs. The implied values of reliability in model (3b) are a little higher than those for route choice only, whereas value of time is about 25% higher.

6. Transponder choice

In previous sections, installation of an electronic transponder has been treated implicitly as part of the route choice. This effectively assumes that the two are inherent aspects of a single choice,

Table 10
Mode and route choice (asymptotic *t*-statistics in parentheses)

Independent variable	Mode choice (3a)	Mode & route choice Joint logit (3b)	Mode & route choice Nested logit (3c)
HOV2	−2.202***	−1.623***	−1.672***
	(−3.357)	(−8.090)	(−8.129)
(*y* − 60)*HOV2	0.0122*	–	–
	(1.937)		
(cars-2)*HOV2	−0.441**	−0.381**	−0.384**
	(−2.162)	(−1.965)	(−1.968)
edu0*HOV2	0.899***	0.776**	0.747**
	(2.578)	(2.392)	(2.284)
flex*HOV2	−0.00443	–	–
	(−1.378)		
lane*HOV2	0.553*	–	–
	(1.813)		
HOV3	−3.944***	−2.887***	−3.0107***
	(−3.563)	(−7.898)	(−7.879)
male*HOV3	−0.458	–	–
	(−1.215)		
(dist-37)*HOV3	0.0214**	–	–
	(2.113)		
lang*HOV3	1.131**	0.967*	0.994*
	(2.134)	(1.893)	(1.931)
wksize*HOV3	0.00384**	0.00351**	0.371**
	(2.171)	(2.028)	(2.120)
lane*HOV3	0.937**		
	(2.302)		
Lane	–	−3.206***	−4.000463***
		(−3.282)	(−3.560)
*y**lane	–	0.0192***	0.0184***
		(3.822)	(3.656)
lang*lane	–	−1.0552**	−0.946**
		(−2.441)	(−2.177)
flex*lane	–	0.00487*	0.00503*
		(1.807)	(1.864)
dist*lane	–	0.0543*	0.0560**
		(1.909)	(1.976)
dist^2*lane	–	0.000513*	0.000532*
		(−1.841)	(−1.919)
medt	–	−0.206**	−0.152*
		(−2.574)	(−1.737)
dmp90	–	−0.285***	−0.252***
		(−4.277)	(−3.617)
male*dmp90	–	0.177***	0.176***
		(2.961)	(2.956)
cost	−0.431	−0.368***	−0.428***
	(−1.036)	(−2.975)	(−3.252)
ρ_r	–	–	−0.327

Table 10 (Continued)

Independent variable	Mode choice (3a)	Mode & route choice Joint logit (3b)	Mode & route choice Nested logit (3c)
			(−0 374)
N	336	333	333
Log likelihood	−256 217	−462 998	−461 9537
Pseudo R^2	0 3059	0 2240	0 2258
VOT (\$/h)[a]	–	24 52	15 55
VOR (\$/h)[a]			
Male	–	12 85	7 78
Female	–	33 92	25 79

[a] Adjusted for understatement of time differences, see text and note to Table 4

that would be appropriate, for example, if getting a transponder to use the toll road were as simple as getting a fare card to ride a subway But actually, the act of installing a transponder and setting up the associated financial account requires an explicit effort and may have its own random determinants, at least partly independent of those connected with route choice If that is true, a better description of behavior is obtained by treating transponder installation as an explicit choice dimension.

As a starting point, we first take it as the only choice Hence the first model in Table 11 is of transponder choice alone, conditional on mode (indicated by the dummy variable "pool" for either HOV2 or HOV3) and time of day, but taking no explicit account of the travel benefits that can be achieved with a transponder This is the converse of the way route choice was modeled in Section 2, as a reduced form with transponder choice implicit, here, it is route choice that is implicit The model shows that high income, female gender, and carpooling all strongly increase the willingness to install a transponder. So does speaking English, although with less statistical certainty

The next two models consider transponder and route choice to be jointly determined There are three alternatives no transponder, transponder using free route, and transponder using toll route In these models, carpool is allowed to influence the system through its effect on route choice via the cost variable, rather than through the alternative-specific constant for transponder choice as in model (4a) Model (4b) is joint logit, whereas (4c) is nested logit with transponder choice being the upper-level choice, as shown in Fig 1. The inclusive value coefficient in (4c), however, is indistinguishable from one, suggesting that the joint logit model (4b) is adequate

Experimentation showed that when both choices are considered explicitly in this way, the influence of income, gender, and language that we detected earlier occurs more in connection with transponder choice than with route choice For this reason they are interacted with the alternative-specific dummy for transponder, rather than for route, in the models shown here The remaining socio-economic variables that explained route choice in earlier models (particularly model 1g) are no longer statistically significant, except for work-hour flexibility In particular, trip distance has lost its explanatory power.

Model (4d) goes further by considering three choices simultaneously. transponder, route, and mode. It is conditional on time of day, and has nine alternatives – three modes for each of the

Table 11
Transponder, route, and carpool choice (asymptotic *t*-statistics in parentheses)

Choice	Transponder choice	Transponder & route		Transponder & route & carpool
Independent variable	Reduced form (4a)	Joint logit (4b)	Nested logit (4c)	Joint logit (4d)
Tag	0.283	−0.862**	−0.874	−0.923**
	(0.748)	(−2.099)	(−1.126)	(−2.221)
y*tag	0.024***	0.0239***	0.0239***	0.0236***
	(4.313)	(4.087)	(4.085)	(4.000)
male*tag	−0.896**	−0.527	−0.525	−0.453
	(−3.055)	(−1.554)	(−1.423)	(−1.326)
pool*tag	0.801**	–	–	–
	(2.339)			
lang*tag	−0.669*	−0.766*	−0.767*	−0.680
	(−1.729)	(−1.859)	(−1.840)	(−1.589)
Lane	–	−0.789	−0.785	−1.159
		(−0.925)	(−0.653)	(−1.377)
flex*lane	–	0.00567**	00564*	0.00525**
		(2.228)	(1.810)	(2.013)
dist*lane	–	0.0388	0387	0.0451*
		(1.444)	(1.147)	(1.674)
dist^2*lane	–	−0.000381	−0.000380	−0.000421
		(−1.464)	(−1.211)	(−1.613)
HOV2	–	–	–	−1.593***
				(−8.007)
(cars-2)*HOV2	–	–	–	−0.371*
				(−1.910)
edu0*HOV2	–	–	–	0.764**
				(2.358)
HOV3	–	–	–	−2.675***
				(−7.871)
wksize*HOV3	–	–	–	0.00315*
				(1.857)
medt	–	−0.150*	−0.150*	−0.177**
		(−1.954)	(−1.774)	(−2.281)
dmp90	–	−0.218***	−0.217***	−0.247***
		(−3.327)	(−3.068)	(−3.707)
male*dmp90	–	0.102	0.102	0.130**
		(1.616)	(1.606)	(2.007)
cost	–	−0.357***	−0.356**	−0.339***
		(−2.589)	(−2.464)	(−2.773)
ρ	–	–	1.00948*	–
			(1.927)	
N	361	341	341	332
Log likelihood	−166.367	−310.232	−310.232	−567.064
Pseudo R^2	0.3351	0.2675	0.2675	0.2226
VOT ($/h)[a]	–	18.40	18.45	22.87
VOR ($/h)[a]	–	–	–	–
Male	–	14.23[b]	14.15[b]	15.12
Female	–	26.74[b]	26.70[b]	31.91

[a] Adjusted for understatement of time differences, see text and note to Table 4.

[b] Male–female difference not significant at 5% level in this model.

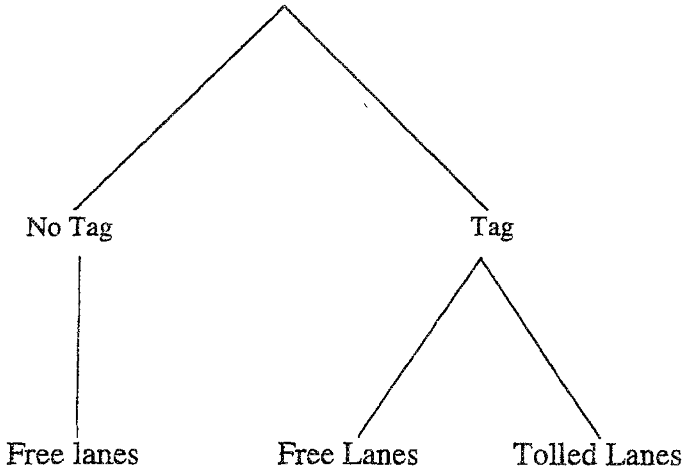

Fig 1 Tree structure for nested logit model

three alternatives of Models (4b)–(4c) We also tried two nested logit models, one with mode conditional on route and transponder choice, the other vice versa, but in both cases the inclusive value coefficients were close to one so the model was indistinguishable from joint logit[11]

Models (4b)–(4d) suggest that adding transponder choice explicitly has only a minor effect on estimated VOT and VOR Overall we regard Model (4d) as our best model, and as providing the most trustworthy estimate of these quantities

7. Conclusion

Table 12 compares the best estimates of VOT and VOR from the five combinations of choices we have considered With route choice alone, the value of median travel-time is about $19/h, or 61% of the sample average wage rate This applies to congested travel, for which the value is probably has a higher value than for uncongested time The VOR, defined as the 90th percentile travel-time minus the median, is 38% of this average wage for men, and 91% for women

Including time of day as one of the endogenous decisions, as in Model (2d), greatly reduces the estimates of VOT and VOR Unfortunately, the accuracy of these estimates is doubtful because we had to make heroic assumptions to compute how the travel times vary across time-of-day alternatives.

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[11] We re-estimated a model almost identical to Model (4d) using the route-choice weights of Table 1, verifying that the coefficients of interest were not affected appreciably (the cost coefficient changed imperceptibly, whereas the coefficients on median travel time and on travel-time dispersion went up 4% and 3%, respectively) In fact, no coefficients changed appreciably except for the route-choice constant We also re-estimated two nested-logit versions of the same model, using route-choice weights, these models showed a similar robustness except that the two-person carpool constant (coefficient of HOV2) became larger in magnitude by 0 27, consistent with the theoretical result that nested logit is more vulnerable to choice-based sampling than joint logit

Table 12
Implied values of travel time and reliability[a]

Model	Type of choice	Value of time ($/h)	Value of reliability ($/h)	
			Male	Female
(1g)	Route	19 22	11 90	28 72
(2d)	Route & time of day	4 74	5 72[b]	7 42[b]
(3b)	Route & mode	24 52	12 85	33 92
(4b)	Transponder & route	18 40	14 23[b]	26 74[b]
(4d)	Transponder, mode, & route	22 87	15 12	31 91

[a] Adjusted for understatement of time differences, see text and note to Table 4
[b] Male–female difference not significant at 5% level in this model

The other models show that most of our results are reasonably robust to how the simultaneous decisions about mode and transponder choice are handled Accounting for mode choice raises VOT by about 28%, with little effect on VOR Accounting explicitly for transponder choice reveals that the transponder installation decision has its own determinants, distinct from those of the daily decision of whether or not to use the transponder, but accounting for this does not affect VOT and VOR very much

We regard Model (4d), which accounts explicitly for both transponder and mode choice, as the most trustworthy of those presented This model produces a VOT of $22 87 per hour and VOR of $15 12 per hour for men and $31 91 per hour, all from a sample with weighted average wage rate equal to $31 69 per hour

All the models show interesting and mostly plausible variations in the propensities for various choices with respect to personal characteristics In particular, several factors are brought to light by our unusual opportunity to observe route choice when one route is subject to time-of-day pricing Income, gender, and language seem especially to affect the willingness to undertake the fixed cost of installing a transponder, whereas work-hour flexibility and total trip distance seem to influence the daily decision of which route to take It will be interesting to see if further research can identify more explicitly the reasons why so many people who have transponders make different decisions from day to day as to whether to use them

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