Australasian Transport Research Forum 2016 Proceedings
16 – 18 November 2016, Melbourne, Australia
Publication website: http://www.atrf.info

Estimating the value of congestion under road pricing schemes

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Abstract

The answer to the environmental and economic problems that traffic congestion poses in large urban areas is often road pricing. While the literature about mode and route choice has focused on the value of congestion and the literature about road pricing has focused on economic aspects of road pricing, a missing link is the evaluation of congestion under road pricing schemes. Accordingly, this study contributes to the literature by estimating the value of congestion of drivers under road pricing schemes from a route choice experiment.

The experiment was performed in Copenhagen, where GPS devices traced the trips of 240 drivers that were assigned to three groups. Each group drove without any pricing scheme and either (i) a cordon toll scheme, (ii) a low pay-per-km scheme, or (iii) a high pay-per-km scheme. The GPS traces were map-matched, choice sets were generated, and mixed logit models were estimated to evaluate the value of congestion as the ratio between the parameters for congested and free flow travel time. Results show that higher heterogeneity was observed for the cordon toll and the low pay-per-km schemes, but also that the value of congestion not only increases significantly under road pricing schemes, but also reaches the highest values when a cordon toll pricing scheme is imposed.

1. Introduction

An answer to the environmental and economic problems introduced by traffic congestion in large urban areas is the introduction of road pricing. While the literature about road pricing has focused on its economic aspects (e.g., Eliasson, 2009; Fosgerau & van Dender, 2013) and the literature about mode and route choice has posed attention towards the estimation of the value of congestion (e.g., Rose et al., 2008; Abrantes and Wardman, 2011; Wardman, and Ibañez, 2012; Prato et al., 2014), this study contributes to the debate by estimating the value of congestion of drivers under road pricing schemes from a route choice experiment.

The value of congestion is defined as the ratio between the value of time (VoT) in congested conditions with respect to the VoT in free flow conditions. A consensus has been reached about the value of congestion varying across traffic conditions as drivers feel more frustrated and endangered when more vehicles are on the road (Fosgerau et al., 2007; Wardman and Ibañez, 2012). However, a consensus has not been reached about the quantification of the value of congestion. Its first estimate was about 1.30 according to a forty-year-old report that compared the estimated coefficient of auto congestion time with the one of auto non-congestion time (Train, 1976). Its second estimate was between 1.28 and 1.46, following a stated preference (SP) study in the UK about ten years later (Wardman, 1986). Since then, it is safe to say that a consensus has not been reached about the actual value of congestion, as estimates vary between about 1.00 and over 2.50, although agreement exists about commuters having the highest evaluation of congested time and SP studies being preferred for the estimation regardless of the inherent biases of travellers not experiencing any actual congestion. A recent revealed preference (RP) study from GPS data observations has assessed a value of congestion at about 1.50 in the peak period with a 1.36-1.60 interval at the 90% confidence level, and 1.26 in the off-peak period with a 1.21-1.31 interval at the 90% confidence level (Prato et al., 2014). Not only this recent study evaluated the value of congestion from actual behaviour, but also confirmed the hypothesis that the value of congestion varies across traffic conditions.

The current study looks further in the aforementioned direction by estimating the value of congestion under different road pricing schemes thanks to the observation of actual route choice behaviour of drivers participating in a route choice experiment in Copenhagen (Denmark). GPS devices traced the trips of 240 drivers that were given an initial amount of money that they would have to give back when driving through the road pricing schemes. Each driver drove both in control conditions, namely without any pricing, and one of three schemes: (i) a cordon toll scheme, (ii) a low pay-per-km scheme, or (iii) a high pay-per-km scheme. Details about the experiment are provided by Nielsen (2004). The GPS traces were map-matched to the network of the Danish National Transport Model (Landstrafikmodel, LTM) adapted to the time of the experiment. Then, choice sets were generated via a doubly stochastic generation method that accounts for heterogeneity across route perception and travellers' preferences. Lastly, route choice models were estimated via a mixed path size logit that accounts for similarity across alternatives and heterogeneity across travellers. The value of congestion was computed as the ratio between the parameters for congested and free flow travel time, as the free flow and congested travel times were available from the LTM for the demand and network at the time of the experiment.

The current study contributes to the literature by providing evidence about drivers' perception of congestion when measures for its reduction are implemented via the observation of actual route choice behaviour thanks to a significant effort in big data collection and modelling. The remainder of the paper is organized as follows: section 2 describes the data collection, the data manipulation and the route choice modelling techniques that were applied in the current study; section 3 illustrates the results of the route choice models and the calculation of the value of congestion in the different road pricing schemes; section 4 summarises the conclusions from the current study and presents avenues for further research.

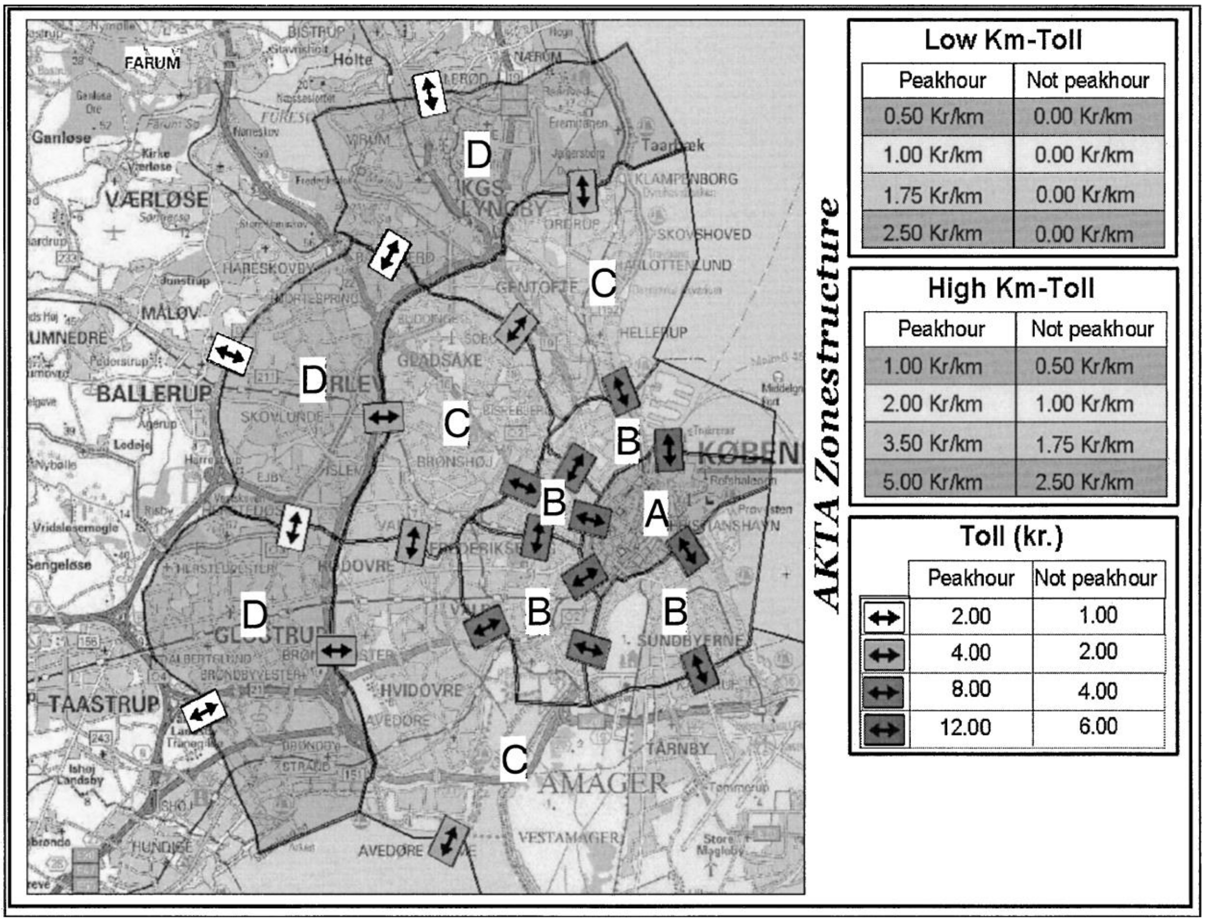
2. Methods

2.1. Data

The AKTA (Anstrengelse af KørselsTrafiksAfgifter, in English Experiment on Road Pricing) experiment involved 500 drivers who received money and were instructed to drive while being exposed to different road pricing schemes over a period of 8 to 12 weeks in the Copenhagen Region. The three road pricing schemes were (i) a cordon toll scheme, (ii) a low pay-per-km scheme with pricing being charged only in the peak hours, and (iii) a high pay-per-km scheme with pricing charged the entire day and double the amount in peak hours. Figure 1 shows the study area and the implementation of the road pricing schemes. The value of the experiment lies in its behavioural realism because of the observation of actual route choice behaviour, the involvement of actual money transactions, and the definition of plausible road pricing schemes on the basis of existing ones (see, for details, Nielsen, 2004).

The current study focuses on a sample of 240 drivers because of technical and behavioural reasons. From the technical perspective, this study did not trust a significant amount of the data given the documented problems of loss of signal, inaccuracy of coordinates, trip segmentation and general malfunctioning for about 46% of the drivers (Nielsen, 2004). From the behavioural perspective, this study considered route choices from drivers who drove both within one of the three road pricing as well as in the control conditions for at least 20 trips in each scheme. Accordingly, the control sample is composed of 240 drivers and each of the three samples related to the three road pricing schemes is composed of 80 drivers.

Figure 1: Study area for the route choice experiment (source: Nielsen, 2004) [1]



Low Km-Toll

Peakhour	Not peakhour
0.50 Kr/km	0.00 Kr/km
1.00 Kr/km	0.00 Kr/km
1.75 Kr/km	0.00 Kr/km
2.50 Kr/km	0.00 Kr/km

High Km-Toll

Peakhour	Not peakhour
1.00 Kr/km	0.50 Kr/km
2.00 Kr/km	1.00 Kr/km
3.50 Kr/km	1.75 Kr/km
5.00 Kr/km	2.50 Kr/km

Toll (kr.)

	Peakhour	Not peakhour
↔	2.00	1.00
↔	4.00	2.00
↔	8.00	4.00
↔	12.00	6.00

Route choice behaviour was observed for the 240 drivers by processing their GPS traces corresponding to their routes. A version of the LTM network at the time of the study was used for map-matching the GPS traces for obtaining the initial routes. The LTM network consisted of about 34,000 links covering the entire country and was preloaded with traffic volumes from the LTM traffic assignment. The free flow and congested travel times were given for each link by the results of the traffic assignment for 10 time periods during the day (see, for details, Prato et al., 2014). The cost of driving for each link was calculated as the product of its length by the marginal cost of driving, which accounted for the consumption of fuel, oil, tires, and battery, and amounted at 0.70 DKK/km (about 0.15 AUD/Km) in 2004 as defined by the Danish Ministry of Transport.

Once the routes were map-matched, a post-processing procedure removed (i) routes that were shorter than 1 km for the likely impossibility to generate alternative routes, and (ii) routes that were filled with a shortest path linkage between matched parts because of gaps in the GPS traces. The map-matching and the post-processing resulted in 65,846 observed routes: 31,684 in the control group, 7,781 in the cordon toll group, 10,431 in the low pay-per-km group, and the remaining 15,950 in the high pay-per-km group.

2.2. Choice set generation

After obtaining the 65,846 observed routes, alternatives routes were generated prior to route choice models being estimated according to a traditional two-stage approach (see Prato, 2009). The search for behavioural plausibility and the need for computational efficiency

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[1] In 2004, 1 AUD = 4.55 DKK

suggested to apply a doubly stochastic choice set generation method able to create alternative routes under the assumption that cost perceptions might be erroneous and different across drivers (Nielsen, 2000, Bovy and Fiorenzo-Catalano, 2007).

The choice set generation method required the specification of a generating function with three variables and three error terms (see, e.g., Prato et al., 2014). The three variables were the distance, the free flow travel time and the congested travel time from the LTM assignment. The first error term was related to the distance to account for the error in perceptions, and the additional error terms were related to the two travel time components to account for the heterogeneity in the error in perceptions of free flow and congested travel time. The first error term was assumed to be gamma distributed to guarantee additivity across links as well as non-negative distances being randomly drawn. The additional error terms were assumed to be lognormal distributed to guarantee non-positive preference for travel time being randomly extracted. The utility functions from the LTM assignment were used for the parameters and the error terms, and random values were extracted 100 times from the respective distributions for each observation *n* and for the time period when the observation *n* occurred.

The post-processing of the generated routes consisted of three phases: (i) compile the choice set for each observation; (ii) remove observations where the choice set generation did not produce routes behaviourally consistent with the observed one; (iii) compute the variables for model estimation. The first phase identified unique routes within the 100 generated routes to compile the choice set. The second phase verified the behavioural consistency of the generated routes by measuring the coverage COV_g of the observed route with respect to an acceptable threshold (see Prato, 2009):

$$COV_g = \frac{\sum_{n=1}^{N} I\left(O_{ng} \geq \delta\right)}{N_p} = \frac{\sum_{n=1}^{N} I\left(\frac{L_{ng}}{L_n} \geq \delta\right)}{N_p} \tag{1}$$

where $I(\bullet)$ is a function equal to one when its argument is true and zero when it is false, L_n is the length of the observed route *n*, L_{ng} is the overlapping length between the observed route *n* and the generated route *g*, O_{ng} is the overlap percentage between the observed route *n* and the generated route *g*, N_p is the number of observations at the second post-processing phase, and δ is an overlap threshold between generated and observed routes. In line with existing literature, an 80% threshold was considered for deeming the generated choice sets consistent with the observed routes (see Prato, 2009).

The third phase computed the following variables for each observed and alternative routes for observation *n* for the time period when the observation *n* occurred: (i) free flow time, (ii) congested time, (iii) travel cost, (iv) number of left turns, and (v) number of right turns. The first two variables were additive across the links composing the route, the third variable included both the additive cost of driving on the links and the road pricing cost, while the last two variables were computed from the topography of the network. It should be noted that Denmark follows right-hand driving, which implies that left turns are expected to have higher penalties than right turns.

2.3. Route choice model

The utility U_{nj} of each route *j* within the choice set of observation *n* was expressed as the sum of a deterministic part V_{nj} and a stochastic part ε_{nj}. The deterministic part V_j of the utility function had a linear-in-parameters specification:

$$V_{nj} = \beta_{fft} fftime_{nj} + \beta_{congt} congtime_{nj} + \beta_{\mathrm{cost}} \mathrm{cost}_{nj} + \beta_{left} left_{nj} + \beta_{right} right_{nj} \tag{2}$$

where, for each route j of observation n, $fftime_j$ is the free flow time, $congtime_j$ is the congested time, $cost_j$ is the cost, $left_j$ is the number of left turns, $right_j$ is the number of right turns, and the β's are parameters to be estimated.

The stochastic part ε_{nj} of the utility function was assumed to be Gumbel distributed, and the probability of selecting the observed route i in the choice set C_n of observation n assumed the formulation of the path size correction logit (PSCL) model to account for similarities across alternative routes (Bovy et al., 2008):

$$P_{ni} = \frac{\exp\left(V_i + \beta_{psc} psc_i\right)}{\sum_{j \in C_n} \exp\left(V_j + \beta_{psc} psc_j\right)} \tag{3}$$

where psc_j is the path size correction and β_{psc} is a parameter to be estimated. The path size correction psc_j captures the similarity across alternative routes within choice set C_n (Bovy et al., 2008):

$$psc_j = -\sum_{a \in \Gamma_j} \left(\frac{L_a}{L_j} \ln \sum_{j \in C_n} \delta_{aj} \right) \tag{4}$$

where L_j is the length of route j, L_a is the length of link a, Γ_j is the set of links belonging to route j, and δ_{aj} is the link-path incidence dummy (equal to one if links a belongs to route j and zero if it does not).

A mixed path size correction logit (MPSCL) was formulated for the current study to allow for heterogeneity across drivers in their preferences for the route characteristics. The probability of selecting the observed route i in the choice set C_n of observation n assumed then the following formulation:

$$P_{ni} = \int \frac{\exp\left(V_{ni} + \beta_{psc} psc_i\right)}{\sum_{j \in C_n} \exp\left(V_{nj} + \beta_{psc} psc_j\right)} f\left(\beta \middle| \theta\right) d\beta \tag{5}$$

where the β's are random parameters that were distributed with probability density functions $f(\beta | \theta)$ characterized by distribution parameters θ, and the probability function needs to be integrated over the distribution of the β's. Parameters for the free flow time, congested time and travel cost were tested for bounded distributions in order to avoid unrealistic preferences for higher time and cost of routes. Parameters for the left and right turns were tested for both bounded and unbounded distributions as not all drivers might have a preference for the most direct route.

Given that the probability of selecting the observed route i in the choice set C_n of observation n did not have a closed-form expression, the parameters were estimated by simulated maximum likelihood:

$$SLL = \sum_{n=1}^{N} \sum_{j=1}^{J} d_{ni} \ln \left\{ \frac{1}{R} \sum_{r=1}^{R} \left[\frac{\exp\left(V_{ni}^r + \beta_{psc} psc_i\right)}{\sum_{j \in C_n} \exp\left(V_{nj}^r + \beta_{psc} psc_j\right)} \right] \right\} \tag{6}$$

where SLL is the simulated log-likelihood, N is the number of observations, d_{ni} is equal to 1 if driver n has chosen route i and 0 otherwise, r is one of R random draws for the simulation of the multi-dimensional integral, and the superscript r represents the instance of a draw from the distribution of the random parameters β's that realizes the utility function V_{nj}^r.

The parameters β's, θ and β_{psc} were restricted not to vary across different observations of the same driver and were estimated in the current study by using 1000 random draws from a

Modified Latin Hypercube Sampling (MLHS) method (Hess et al., 2006) in the freeware software Biogeme (Bierlaire, 2008).

As the objective of the current study was the calculation of the value of congestion under different road pricing schemes, the initial sample was divided into four samples: 31,684 observations in the control group, 7,781 in the cordon toll group, 10,431 in the low pay-per-km group, and the remaining 15,950 in the high pay-per-km group. As the road pricing schemes were different between peak and off-peak hours, each of the four samples was further divided into two according to the aforementioned division. For each model, the value of congestion was calculated as the ratio between the estimates of the parameters β_{congt} and β_{fft} and, given the distributions of these two parameters, the means, standard deviations and confidence intervals of the different values of congestion were calculated analytically as illustrated by Daly et al. (2012).

3. Results

3.1. Observed and generated routes

The results from the choice set generation and the route choice model estimation are presented for eight samples resulting from observing initial results. In fact, 10 time periods from the LTM were initially considered: similarities were observed in terms of congestion levels in two periods in the morning peak hours (i.e., 7am-8am and 8am-9am) and three periods in the afternoon peak (i.e., 3pm-4pm, 4pm-5pm, 5pm-6pm), while similarities were also observed in the midday off-peak period (i.e., 9am-3pm) and the evening off-peak period (i.e., 6pm-9pm). Accordingly, the eight samples were for the peak and the off-peak hours of each of the control and road pricing schemes (i.e., control, cordon, low pay-per-km, high pay-per-km).

The choice set generation method generated 100 alternative routes for the 65,846 observations in about 9 hours in the large-scale LTM network, thus showing reasonable computational efficiency in the programming in C# of an ArcGIS module for route generation. Given the 65,846 observed routes, the choice set generation method produced at least 1 alternative route for all of them, most likely because they were all longer than 1 km. Table 1 presents the sample characteristics for the four samples in the peak period, and table 2 shows the same characteristics for the four samples in the off-peak period.

Table 1: Observed routes and choice set generation characteristics for the peak period

Variable	Control	Cordon	Low-km	High-km
Distance (mean, km)	7.28	7.43	8.89	6.76
Distance (st.dev., km)	8.40	10.22	11.15	8.67
Free flow time (mean, min)	7.69	7.77	9.04	7.04
Free flow time (st.dev., min)	6.67	7.32	8.67	6.30
Congested time (mean, min)	9.46	9.59	11.06	8.69
Congested time (st.dev., min)	8.33	8.71	10.62	9.28
Price (mean, DKK)	0.00	5.27	5.04	8.51
Price (st.dev., DKK)	0.00	7.07	5.92	9.93
Covered observations	8,467	1,781	2,371	4,035
Total observations	10,862	2,509	3,255	5,242
Coverage (%)	88.3%	84.3%	85.3%	87.7%
Number of alternatives (mean)	41.2	30.4	36.0	31.2
Number of alternatives (st.dev.)	28.4	20.5	29.9	25.8

Table 2: Observed routes and choice set generation characteristics for the off-peak period

Variable	Control	Cordon	Low-km	High-km
Distance (mean, km)	7.14	7.85	7.74	6.62
Distance (st.dev., km)	9.93	11.39	11.35	9.49
Free flow time (mean, min)	7.27	7.98	7.67	6.68
Free flow time (st.dev., min)	7.10	8.16	7.94	6.64
Congested time (mean, min)	7.73	8.47	8.15	7.02
Congested time (st.dev., min)	7.48	8.51	8.34	6.91
Price (mean, DKK)	0.00	2.94	0.00	3.59
Price (st.dev., DKK)	0.00	4.12	0.00	4.02
Covered observations	16,942	4,066	5,857	8,569
Total observations	20,822	5,272	7,176	10,708
Coverage (%)	90.2%	87.8%	90.3%	89.5%
Number of alternatives (mean)	36.7	42.0	34.0	31.3
Number of alternatives (st.dev.)	27.8	30.5	28.4	25.8

Looking at the figures in the tables, it is apparent that drivers performed more trips in the off-peak hours, as well as more trips in the high pay-per-km scheme and less trips in the cordon scheme. Although changing the departure time for the trips and the transport mode is out of the scope of the current analysis focusing on the value of congestion, evidence about behavioural change is discussed by Nielsen (2004).

Looking at the same figures, it appears that the coverage with an 80% overlap threshold was quite high for all the eight samples, although slightly higher in general for the off-peak period samples (87.8%-90.3%) with respect to the peak period ones (84.3%-88.3%). This might suggest that some of the routes taken when road pricing was implemented were less consistent with the routes generated regardless of the fact that the choice set generation procedure was the same for all the sample.

The length of the routes was comparable across the samples, also given the high heterogeneity in terms of both distance and time. The number of unique routes within the generated choice sets was between 2 and 100, with a mean number of alternatives between 30.4 and 40.2, and a standard deviation of the number of alternatives between 20.5 and 30.5, and the comparable average in the number of alternatives is likely related to the comparable length of the routes. The average level of congestion on the routes is expectedly higher in the peak periods (22.3%-23.4%) with respect to the off-peak period (5.1%-6.4%).

3.2. Route choice model estimates

The estimation of the MPSCL models for the four peak sample and the four off-peak samples tested several options for the distributions of the parameters. Lognormal, constrained triangular and Sb Johnson distributions were considered for free flow time, congested time and travel cost, while normal and triangular distributions were considered for left and right turns. The different specifications were compared for each sample via log-likelihood tests, and the best fit was obtained for all samples by a model that accounted for heterogeneity in the preferences of drivers for free flow time and congested time with a lognormal distribution, while heterogeneity for cost, left turns and right turns was not found to be significant and hence fixed parameters were estimated for these variables. Accordingly, table 3 presents the MPSCL model estimates for the samples relative to the peak period of the four groups, while table 4 presents the MPSCL model estimates for the samples relative to the off-peak period of the four groups.

From a behavioural perspective, the parameters show as expected that drivers are utility maximisers. In fact, drivers minimise free flow time and congested time while driving in both peak and off-peak hours regardless of the imposition of a road pricing scheme. Drivers minimise also travel cost and turns, and appear more sensitive to left turns with respect to right turns in a right-hand driving country. Also, the parameters of the path size correction penalise the utility of routes with high similarity to alternative ones as expected from a theoretical perspective.

The estimates of the four models for the peak hours in table 3 show that the preference for less expensive and more direct routes is fairly comparable across the four samples, although caution should be posed in the interpretation because of possible scale differences that are not taken into account when estimating models on different samples. The preference for shorter routes in terms of time shows different sensitivity to the free flow and the congested components. For the models of the peak hours, the means of the four lognormal distributions for the free flow time are respectively -0.318, -0.479, -0.452 and -0.511 for the control, cordon, low pay-per-km and high pay-per-km samples, while the standard deviations for the same four distributions are respectively 0.076, 0.114, 0.114 and 0.124 for the same four groups. The means of the four lognormal distributions for the congested time are respectively -0.457, -0.849, -0.805 and -0.910 for the control, cordon, low pay-per-km and high pay-per-km samples, while the standard deviations for the same four distributions are respectively 0.129, 0.221, 0.205 and 0.238.

Table 3: MPSCL estimates for the peak hours

	Control		Cordon		Low-km		High-km	
Variable	est.	t-stat	est.	t-stat	est.	t-stat	est.	t-stat
Free flow time (μ, min)	-1.173	-3.90	-0.764	-2.39	-0.824	-4.14	-0.700	-4.38
Free flow time (σ, min)	0.236	3.46	0.235	2.27	0.248	2.44	0.239	2.75
Congested time (μ, min)	-0.821	-4.25	-0.197	-2.03	-0.249	-4.58	-0.127	-2.71
Congested time (σ, min)	0.276	3.45	0.257	1.80	0.251	3.58	0.258	2.53
Cost (DKK)	-0.205	-5.06	-0.248	-3.60	-0.243	-5.32	-0.257	-4.31
Left turns (unit)	-0.641	-44.18	-0.664	-19.45	-0.667	-33.55	-0.711	-29.92
Right turns (unit)	-0.475	-40.21	-0.477	-19.86	-0.485	-33.44	-0.500	-25.79
Ln (path size)	0.691	25.84	1.140	18.57	0.754	24.22	0.913	23.41
Number of drivers		9590		2114		2778		4599
Number of observations		240		80		80		80
Null log-likelihood		-16472.77		-3740.70		-4565.72		-7265.11
Final log-likelihood		-11770.12		-2317.09		-3224.95		-4764.23
Adjusted rho-square		0.285		0.378		0.292		0.343

The estimates of the four models for the off-peak hours in table 4 illustrate that the preference for less expensive and more direct routes is fairly comparable across these four samples as well. Actually, the ratios between left and right turns appear fairly comparable across all eight models and so seem to be the ratios between left turns and cost. The preference for shorter routes is confirmed, although the values of the distributions appear different with respect to the previous four models in that there seems to be less variation (although again, caution should be used in the interpretation because of possible scale differences that are not considered when estimating models on different samples). For the models of the off-peak hours, the means of the four lognormal distributions for the free flow time are respectively -0.198, -0.231, -0.220 and -0.241 for the control, cordon, low pay-per-km and high pay-per-km samples, while the standard deviations for the same four distributions are respectively 0.036, 0.050, 0.054 and 0.046 for the same four groups. The means of the four lognormal distributions for the congested time are respectively -0.238, -0.277, -0.262 and -0.287 for the control, cordon, low pay-per-km and high pay-per-km samples, while the standard deviations for the same four distributions are respectively 0.051, 0.062, 0.060 and 0.067.

Table 4: MPSCL estimates for the off-peak hours

	Control		Cordon		Low-km		High-km	
Variable	**est.**	**t-stat**	**est.**	**t-stat**	**est.**	**t-stat**	**est.**	**t-stat**
Free flow time (μ, min)	-1.638	-12.73	-1.488	-2.19	-1.537	-3.70	-1.448	-4.01
Free flow time (σ, min)	0.183	4.86	0.213	1.79	0.208	2.40	0.221	2.16
Congested time (μ, min)	-1.458	-5.31	-1.308	-2.11	-1.365	-5.13	-1.274	-3.84
Congested time (σ, min)	0.213	1.94	0.222	2.30	0.227	3.28	0.230	1.90
Cost (DKK)	-0.199	-5.00	-0.209	-3.03	-0.213	-5.64	-0.210	-6.21
Left turns (unit)	-0.628	-57.02	-0.641	-24.31	-0.647	-48.82	-0.680	-32.98
Right turns (unit)	-0.465	-49.74	-0.462	-20.88	-0.463	-41.10	-0.483	-44.55
Ln (path size)	0.581	32.29	0.728	17.22	0.584	22.67	0.769	28.74
Number of drivers	18782		4630		6483		9579	
Number of observations	240		80		80		80	
Null log-likelihood	-30731.77		-7977.42		-10351.66		-14834.70	
Final log-likelihood	-21798.24		-5447.89		-7537.08		-10373.51	
Adjusted rho-square	0.290		0.316		0.271		0.300	

3.3. Value of congestion under road pricing schemes

Estimates of the MPSCL models allowed calculating the VoT for free flow time and congested time and hence the values of congestion for the eight samples, as presented in tables 5 and 6.

The mean values of the VoT from the MPSCL models for the peak hours show that the VoT of both free flow and congested time are higher with respect to the off-peak hours, most likely because of two reasons: (i) drivers in the peak hours are more likely to commute and hence are more sensitive to arrive on-time, which in turn makes them more sensitive to congestion; (ii) drivers in the peak hours have the additional cost of the road pricing scheme, which in turn in the off-peak hours is due only in the cordon and the high pay-per-km scheme and at a lower value. The distribution values of the VoT from the same models show also higher heterogeneity for both free flow and congested time when the road pricing schemes are in place, which suggests that the preferences for the additional cost of the toll are far more diverse across the population than the one for the driving cost. Most relevantly, when considering the average congestion level in the peak hours for each sample (between 22.3% and 23.4%), the VoT is approximately 102.57 DKK/h (about 22.54 AUD/h) for the control sample, 130.60 DKK/h (about 28.70 AUD/h) for the low pay-per-km scheme, 135.15 DKK/h (about 29.70 AUD/h) for the high pay-per-km scheme, and 138.85 DKK/h (about 30.52 AUD/h) for the cordon scheme. When looking at the VoT also by time component, it seems clear that the highest average value is for the cordon scheme, followed by the high pay-per-km and the low pay-per-km schemes.

For the models for the peak hours, the mean values of congestion are equal to 1.44 in the control sample, 1.75 for the low pay-per-km scheme, 1.81 for the high pay-per-km scheme, and 1.86 for the cordon scheme. These findings reveal that road pricing significantly increases the value of congestion, as the differences with the control sample are significant at both the 95% and 90% significance level. Moreover, the value of congestion is significantly higher for the cordon scheme with respect to the low pay-per-km scheme, and statistically the difference is negligible between the cordon and the high pay-per-km scheme.

Table 5: Value of congestion for the peak hours

Variable	Control	Cordon	Low-km	High-km
VOT free flow time (mean, DKK/h)	93.24	115.62	111.86	113.55
VOT free flow time (st.dev., DKK/h)	22.31	27.59	28.17	28.98
VOT congested time (mean, DKK/h)	133.94	215.23	195.73	205.77
VOT congested time (st.dev., DKK/h)	37.72	53.45	50.72	55.76
Value of congestion (mean)	1.44	1.86	1.75	1.81
Value of congestion (90% confidence interval)	1.27 - 1.51	1.81 - 1.88	1.71 - 1.76	1.73 - 1.85
Value of congestion (95% confidence interval)	1.21 - 1.52	1.79 - 1.89	1.70 - 1.77	1.70 - 1.85

The mean values of the VoT from the MPSCL models for the off-peak hours show that the VoT of both free flow and congested time are far more comparable across the control and the road pricing schemes. Also, the distribution values of the VoT from the same models suggest comparable heterogeneity for both free flow and congested time when the road pricing schemes are in place, which suggests that the preferences for the additional cost of the toll are comparable given the limited amount of toll over the driving cost. Most relevantly, when considering the average congestion level in the off-peak hours for each sample (between 5.1% and 6.4%), the VoT is approximately 60.43 DKK/h (about 13.28 AUD/h) for the control sample, 62.52 DKK/h (about 13.74 AUD/h) for the low pay-per-km scheme, 68.15 DKK/h (about 14.98 AUD/h) for the cordon scheme, and 69.65 DKK/h (about 15.31 AUD/h) for the high pay-per-km scheme. When looking at the VoT also by time component, it seems clear that the highest average value is for the high pay-per-km scheme, followed by the cordon scheme and then the two other driving conditions without toll in the off-peak hours.

For the models for the off-peak hours, the mean values of congestion are about 1.20 across the four samples, which is intuitively correct as the low congestion off-peak should be perceived as having the same multiplier regardless of the driving conditions. When looking at the 90% and 95% confidence intervals of the values of congestion for the control, cordon, low pay-per-km and high pay-per-km samples, the differences are not significantly different from zero. The most significant difference is that there is a significant higher value in the peak hours in relation to the implementation of the road pricing scheme.

Table 6: Value of congestion for the off-peak hours

Variable	Control	Cordon	Low-km	High-km
VOT free flow time (mean, DKK/h)	59.65	67.34	61.78	68.98
VOT free flow time (st.dev., DKK/h)	11.01	14.26	12.98	15.42
VOT congested time (mean, DKK/h)	71.85	80.76	73.70	82.22
VOT congested time (st.dev., DKK/h)	15.49	17.87	16.96	19.19
Value of congestion (mean)	1.20	1.20	1.19	1.19
Value of congestion (90% confidence interval)	1.11 - 1.25	1.17 - 1.21	1.13 - 1.22	1.16 - 1.21
Value of congestion (95% confidence interval)	1.09 - 1.26	1.16 - 1.22	1.11 - 1.23	1.15 - 1.21

4. Conclusions

As road pricing acceptability has been extensively debated but comparisons of the value of congestion between schemes have not been previously performed, the findings from the current study propose a fresh perspective for understanding the effects of road pricing schemes in terms of congestion perception from the public.

Given that the results are from a quite realistic experiment where money transactions occurred and actual driving behaviour was observed via GPS tracing, there is value in the findings. While the value of congestion does not vary across the four driving conditions in the off-peak hours, significant differences are found between the control sample and the road pricing schemes in the peak hours. In particular, the values are definitely higher for the cordon scheme, although not conclusively higher with respect to the high pay-per-km scheme. The average values of congestion between 1.44 and 1.88 in the peak hours are in line with previous values from Danish SP studies that estimated values of congestion between 1.31 and 1.65 in congested conditions (Nielsen et al., 2002; Nielsen, 2004; Fosgerau, 2006), as well as previous values from another Danish RP study that calculated values between 1.65 and 2.00 in congested conditions (Rich and Nielsen, 2007). Comparisons for the off-peak hours are not available because none of the aforementioned Danish studies looked outside the peak hours. The estimated values of congestion for the peak hours are in line also with previous findings from the U.K. (Abrantes and Wardman, 2011) and Australia (Rose et al., 2008), although none of the models were estimated while drivers drove in road pricing schemes.

Some limitations of the study should be acknowledged. From the data perspective, the values from the LTM assignment are the best available values for the study, but as in all route choice behaviour studies there is some sort of inconsistency with the actual times at the time of the observation of driving behaviour. However, the current study uses observed route choice behaviour rather than the always problematic SP data and, most importantly, exploits the participation of driving in road pricing schemes. From the model perspective, as in all route choice behaviour studies there is some sort of inconsistency between the choice set generation function and the utility function. However, the current study uses calibrated times for the choice set generation and reasonable assumptions for the model specification.

Summarising, the current study provides valuable information on the value of congestion in different traffic conditions and time periods, and suggests how the values vary across road pricing schemes. As in a previous study about value of congestion and reliability (Prato et al., 2014), the current study shows also how to exploit a great amount of information from increasingly cheaper technology for providing valuable information about congestion in different driving conditions. The congestion multipliers could be used in both planning models and simulation models to test different solutions for road pricing, in terms of both the toll scheme and the areas interested by the scheme itself. Further avenues of research could be the estimation of the VoT in value of time space rather than preference space, the consideration of socioeconomic characteristics of the drivers, and the possible consideration of decision paradigms alternative to utility maximisation.

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