CONGESTION CHARGING: THE IMPACTS ON COMMUTER TRAVEL-BEHAVIOUR IN EDINBURGH

Wafaa Saleh [a*], and Séona Farrell [b†]

[a] School of the Built Environment, Napier University, 10 Colinton Road, Edinburgh, EH10 5DT, Scotland, UK.

[b] Transport Research Institute, Napier University, Redwood House, 66 Spylaw Road, Edinburgh, EH11 1JH, Scotland, UK.

Abstract

The objective of this paper is to investigate the potential impacts of implementing variable congestion charging on the peak spreading of departure time choices, taking into account levels of flexibility of individuals. The data for this study was collected as part of a larger survey on the consequences of congestion charging in the city of Edinburgh. Stated choice scenarios on departure time were presented to respondents.

The general investigations of the choice scenarios show that there is a willingness to shift departure times when faced with variable congestion charges. Flexibility as a determinant of availability of departure time alternatives is discussed, investigated and modelled. Variables related to work schedule flexibility, as well as any other relevant variables which affect any individual's choice of departure time have been identified in the models. The calibrated models, which include flexibility parameters that define availability, perform better than the model without such parameters. The models suggest that an individual with limited flexibility is restricted in her ability to change departure times, compared to another with more flexibility who has more alternatives available to her in the departure time choice set. Thus, respondents with lower levels of flexibility are more likely to be constrained in their choice of departure time to work when faced with congestion charges.

Keywords: Departure time choice; Flexibility; Availability of alternatives; Congestion charging; Discrete choice modelling

Topic Area: D6 Travel and Shipper Behaviour Research

1. Introduction

A congestion charging scheme has the potential to significantly impact on travel behaviour, and in particular on departure time switch if the scheme adopted is based on a variable charging structure. If a scheme is introduced with variable charges applied during the day, shifting peaks or peak spreading will be an objective. It is therefore imperative that departure time switch is addressed in the analysis of potential impacts of a charging scheme. One way of investigating the impacts of congestion charging on departure time choice is to use discrete choice models.

Discrete choice analysis is extensively used in the transport field to represent the choices made between a finite set of alternatives, for example, a set of alternative departure times. More specifically, it is often used to investigate and forecast individual travel

* Corresponding author. Tel.: +44-131-455-2371; fax: +44-131-455-2239; email: w.saleh@napier.ac.uk

† Current mailing address: Centre for Transport Research, Department of Civil, Structural and Environmental Engineering, Trinity College, Dublin, Ireland.

behaviour (Ben-Akiva & Lerman (1985) provide a detailed overview of discrete choice analysis).

Departure time choice can be investigated using discrete choice models by dividing the continuous departure time variable into discrete intervals, with each characterised by a different utility level to the commuter. Then the commuter chooses between alternative departure time periods. Cosslett (1977), Abkowitz (1981) and Small (1982) developed multinomial logit (MNL) models to investigate departure time choice. Small (1982) modelled departure time using twelve five-minute intervals. Abkowitz (1981) used the same time intervals but modelled both departure time and mode choices with departure time conditional on choice of mode. McCafferty & Hall (1982) also made use of multinomial logit analysis to model departure time choice, but in this instance for the evening commute from work to home. They tested a number of different ways of discretising departure time choice, and concluded that the best classification for departure time was into three choices: pre-peak, peak and post-peak. Hendrickson & Plank (1984) modelled mode choice and departure time choice, with the assumption that both choices were made simultaneously. Bhat (1998) used a joint model of mode and departure time choice to analyse urban shopping trips. A nested structure was used with mode choice at the higher level and departure time at the lower level of the nest. A MNL formula was used at the higher level and the ordered generalised extreme value (OGEV) formulation in the lower level. However, this model was essentially developed to investigate the performance of MNL logit, nested logit and MNL-OGEV models and furthermore, the study was concerned with shopping trips rather than the commute to work.

Some of the factors in previous studies found to influence choice of departure time (and frequency of departure time changes) have been: travel time, travel costs, marital status and family obligations, income, occupation and the flexibility of work schedule. One crucial determinant of departure time choice for the commute to work is work schedule flexibility. It is evident from the literature that this factor affects departure time choice, e.g., De Palma, Khattak, & Gupta (1997) found that commuters with fixed working hours made fewer changes in their departure times and when changes were made, they were smaller than for flexitime workers. Generally, the definition of flexibility in the literature on departure time/arrival time choice refers only to work schedule flexibility. For example, Abkowitz (1981) defined it as a dummy variable (1 if commuter can be late, and 0 otherwise). Emmerink *et al* (1997) defined a flexibility variable indicating the number of minutes between the latest and earliest work times as allowed by the employer. Whereas, Khattak & De Palma (1997) defined flexibility in terms of ability to arrive late at work (more than 30 minutes late). What is common between all the above definitions is that they rely solely on the respondent's work schedule to define flexibility.

However, these definitions of flexibility, referring only to whether or not a worker has flexible working hours can be considered overly simplistic. Choice of departure time is only one of the numerous decisions made every day and this choice may be conditional on other constraints imposed on an individual such as their stage in the life cycle (e.g. household composition) or way of life (McCafferty & Hall, 1982). This is reiterated by Small (1982) who noted that the coefficients of his departure time model were dependent on factors such as family status, occupation, mode choice and work hour flexibility.

This concept is appealing as it implies that an individual's departure time choice may be constrained by such factors as listed by Small (1982) and McCafferty & Hall (1982) and thus not all departure time alternatives may be available to an individual. McCafferty & Hall (1982) suggested that focusing solely on work schedule constraints for departure time choice would not bring about major changes in departure time patterns. Moreover, defining flexibility merely in terms of work schedule implies that flexibility relates only to arrival time at work or work start time. Perhaps it would be more appropriate to consider flexibility from the perspective of departure time as well as arrival time. This implies that other commitments (other than work start time) should be considered.

Furthermore, it is likely that in terms of departure time choice there are degrees of flexibility (McCafferty & Hall, 1982), i.e. some individuals might have higher levels of flexibility than others. Those will include individuals who have flexible working conditions, individuals who have fewer or no commitments in driving children/ partners to school/work and individuals who have fewer other commitments such as regular activities before work. Individuals with inflexible schedules will have to pay the congestion charges, switch mode, or make other changes, whilst individuals with flexibility in their schedules may be able to avoid the charge (or at least the highest charges) by altering their departure time to work accordingly.

An individual's level of flexibility can be used to define availability of particular departure time alternatives. Choice set definitions and modelling has been discussed widely in the literature mainly in the area of mode choice (e.g. Stopher, 1980; Williams & Ortúzar, 1982; Swait & Ben Akiva, 1986; and Saleh & Bell, 1998). However, the authors are not aware of any similar work in the case of departure time modelling.

This research aims at investigating (by means of a stated choice questionnaire) and modelling the departure time choice implications of the introduction of a variable congestion charging scheme in the city of Edinburgh (UK), taking into account factors that affect departure time choice in addition to work schedule flexibility. Different levels of flexibility have been defined and used to model the availability of departure time alternatives. The rest of the paper is set out in a number of sections. The data collection method and some general results are described in section 2. In section 3 the departure estimation and model results for the base MNL departure time model are presented. Flexibility of departure time choice and thus availability of alternative departure times is discussed in section 4. The modelling of departure time availability (defined from levels of flexibility) is presented in section 5. Discussions and conclusions are presented in section 6.

2. Data description and general analysis

A questionnaire survey was used as a part of a study to investigate the potential impacts of congestion charging on the travel behaviour of Edinburgh commuters. The sample was drawn from employees working in the city centre of Edinburgh. All respondents had to be car owners who drove to work (or owned or had access to a car and could have used it to drive to work), normally departed for work between 06:00 and 10:00am and live within a reasonable* walking distance of a bus stop with services at least once an hour.

There were five sections in the questionnaire. In section one of the questionnaire, respondents provided information about their journey to work, (for example, mode of travel, travel time to work, usual departure time to work, etc.). Respondents supplied information about their work schedules and other commitments (for example, carrying out of activities before/after work) in section two of the questionnaire. In section three respondents were presented with three sets of congestion charging scenarios related to mode choice, departure time choice and combined mode and departure time choice, which

* The term 'reasonable distance' was used instead of a specific walking distance or time because what maybe reasonable to one person is unreasonable to another. Furthermore, if the distance to a bus stop is not perceived as reasonable to a respondent, then the option of taking the bus is not available to them. This was important for other sections of the questionnaire.

are not discussed here. Section four of the questionnaire dealt with the public acceptability of congestion charging and included a set of stated choice scenarios related to revenue allocation. The final section of the questionnaire dealt with the socio-economic characteristics of respondents. This paper concentrates on the congestion charging stated choice experiment for departure time choice.

Only respondents who drove to work (not necessarily just regular drivers) completed the departure time stated choice section of the questionnaire. Thus, 94 of the 211 respondents were eligible to complete the departure time choice scenarios. Each respondent was presented with seven departure time scenarios; thus, a total of 658 observations were possible. After removing respondents who did not provide all required information, e.g. some socio-economic data, the dataset was reduced to 632 observations. From the sample, the majority of respondents (57%) were regular car drivers, followed by regular bus users (who still would have driven to work on some days) at 21% of the observations.

The data available for departure time choice modelling consists of the SC data, plus situational and socio-economic data gathered from the other sections of the questionnaire. Disaggregate choice based models were developed and estimated to investigate the effect of variable congestion charging levels on departure time choice. Three departure time alternatives were defined for the departure time model. Two of the alternatives represented a change in departure time from the respondents' usual departure time for work (earlier than usual and later than usual departure time), while the third alternative represented the respondents' current departure time choice (but with changes in travel time and cost). The variables and variable levels for the choice experiment are shown in Table 1. The changes in departure time ranged from 30 minutes earlier to 30 minutes later than usual. Furthermore, the charging levels varied from £2 to £5.50. The general findings in terms of choices are now presented.

The peak in usual departure times (i.e. before the choice experiment) from home to work of all respondents occurred between 08:00 and 08:29 hours, with 40% of respondents departing in this half hour time period (see Figure 1). The peak hour can be classified as the time period between 07:30 and 08:29 as 69% of respondents usually departed for work in this hour. In general, based on the choices made, there seems to be a willingness to switch departure time when faced with congestion charges. Almost 70% of respondents switched to an alternative departure time (either earlier or later than usual). Initial results show that as a result of variable congestion charges, there has been a 10% decrease in departures during the period 08:00 to 08:29 and a 6% increase in departures during the period 07:00 to 07:29 (see Figure 1). These figures show some evidence of departure time peak spreading. That is, there is a flattening of the peak for the one hour period between 07:30 and 08:30.

The modelling results for departure time choice are presented in the following sections.

Table 1Alternatives and variables in the departure time stated choice experiment

Alternative	Variables of the alternative	Levels of the variable
(1) Depart earlier than usual	(i) Toll	(a) £2 (b) £3.50 (c) £5
	(ii) Departure-time change	(a) 10 minutes earlier (b) 20 minutes earlier (c) 30 minutes earlier
	(iii) Travel time saving	(a) 15% (b) 20% (c) 25%
(2) Depart at the same time as usual	(i) Toll	(a) £3.50 (b) £4.50 (c) £5.50
	(ii) Travel time saving	(a) 15% (b) 20% (c) 25%
(3) Depart later than usual	(i) Toll	(a) £2 (b) £3.50 (c) £5
	(ii) Departure-time change	(a) 10 minutes later (b) 20 minutes later (c) 30 minutes later
	(iii) Travel time saving	(a) 15% (b) 20% (c) 25%

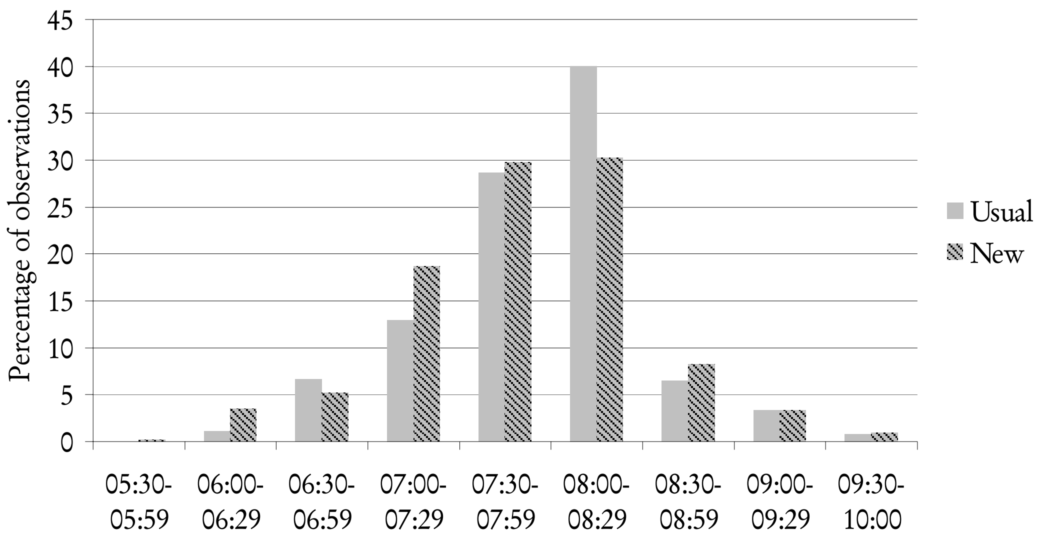

Figure 1 Comparison of usual departure time to work of all respondents and new departure time (as chosen in the stated choice experiment)

3. Departure time model estimation

3.1. The base model

The form of the discrete choice model used in this investigation is determined by the assumptions made about the error (random) terms of the utility function. The multinomial logit (MNL) model has a very simple distribution, which assumes that the error terms are independently, identically Gumbel distributed (also known as type I extreme value), which results in a simple and elegant closed-form model (Bhat & Castelar, 2002). In fact, the density function of the error component of utility is (Train, 2003):

$$f(\varepsilon_{in}) = e^{-\varepsilon_{in}} e^{-e^{-\varepsilon_{in}}} \tag{1}$$

The variance of this distribution is $\pi^2/6$, which implies that the normalisation the scale of utility is required. This results in the following probability function:

$$P_{in} = \frac{e^{V_{in}}}{\sum_{j=1}^{J} e^{V_{jn}}} \tag{2}$$

where P_{in} is the probability that an individual n will choose alternative i, V_{in} is the deterministic component of the utility of alternative i, and J is the number of alternatives. The MNL model has been used in a broad range of travel choice contexts, including destination, mode, and departure time as well as non-travel choice contexts.

The base departure time choice model has been estimated by maximum likelihood using ALOGIT software and describes the choice among three discrete departure time alternatives: 1) earlier than usual departure (ED); 2) same as usual departure (SD); and 3) later than usual departure (LD). The base departure time model was specified with the variables from the SC experiment and further explanatory variables of departure time choice. The SC variables in the model are: toll level, departure time, and travel times, each included as three alternative specific variables. The other variables specified in the model include travel to work related variables, work schedule related variables and socio economic variables, which are described in Figure 2.

Model DP1 is the base departure time choice model (see Table 2). Overall, all of the coefficients have logical signs and are statistically significantly different from zero at the 5% significance level. The model has a ρ^2 of 0.3190 when comparing the base likelihood (with constants) and the final likelihood. Although there are no strict guidelines on what constitutes a 'good' rho-squared value, it is deemed that values between 0.2 and 0.4 are indicative of particularly good model fits (Louviere, Hensher, & Swait, 2000).

The variables from to the stated choice experiment (i.e. the alternative specific TOLL, DEP and TIME variables) all have negative coefficient signs. A negative sign for these variables is as anticipated because it would be expected that a respondent's relative utility would decrease as time and cost increases. A greater disutility is associated with the toll of the ED alternative than for the toll of the other two departure time alternatives. This implies that there is less preference towards paying tolls for earlier than usual departures. The higher coefficient value for departure time change (DEP) for the ED alternative also reveals less preference for switching to an earlier departure time alternative. Generally, it is expected that such preferences would exist, as waking up earlier and leaving home earlier are not as desirable as staying in bed longer and leaving for work later than usual.

However, there may also be negative consequences associated with choosing a later departure time, for example, having to stay at work later and getting home from work later. The SD alternative has the highest coefficient value for travel time implying that increased travel time for this alternative has the greatest disutility followed then by the later than usual departure time alternative. As this alternative represents a respondent's usual departure time to work it is natural that respondents would not be expecting to pay congestion charges in return for longer travel times at this time. Some of the other variables in the model are worthy of comment.

Variable name	Description
TOLL	The toll variable from the stated choice experiment (in £). Alternative specific variables were defined for the earlier (ED), later (LD), and same as usual (SD) alternative.
DEP	The departure time variable in the stated choice experiment (in minutes). Alternative specific variables.
TIME	The travel time variable from the stated choice experiment. Alternative specific variables.
ARRIVAL	Categorical variable: describes respondent's usual arrival time at work. The values of 1 to 6 represent: 07:01-07:30, 07:31-08:00, 08:01-08:30, 08:31-09:00, 09:01-09:30, after 09:30 respectively. Specified for the later alternative (LD).
CARDELAY	Dummy variable: takes the value 1 if travel to work by car and experience at least once a week delays that result in being at least 15 minutes late for work, and 0 otherwise. Specified for the later alternative (LD).
DEP712*	Dummy variable: takes the value 1 if normal departure time is before 07:12am, and 0 otherwise. Specified for the earlier alternative (ED).
DISTANCE	Continuous variable: The number of miles travelled from home to work. Specified for the earlier alternative (ED).
SENIORMGM	Dummy variable: 1 if hold a senior management position, 0 otherwise. Specified for the later alternative (LD).
SCHD	Continuous variable: Schedule delay: New arrival time minus work start time. Workers with flexitime or no fixed hours set to 0. Specified for the earlier alternative (ED).
SINGLE	Dummy variable: takes the value 1 if a single person household, or live in a household with other non-related people, and 0 otherwise. Specified for the earlier alternative (ED).
WILLPAY	Continuous variable: The amount of money a respondent has stated she would pay to avoid being late for work. Specified for the earlier alternative (ED).

Figure 2 Variable definitions for model DP1

For instance, the negative coefficient for the distance variable (DISTANCE) implies that, all else being equal, the greater the distance travelled to work by a respondent the more unlikely she is to switch to an earlier departure time if faced with paying congestion charges. The distance variable was specified for the earlier than usual departure time alternative as it made logical sense to specify it for that alternative. Respondents travelling longer distances to work are normally likely to be departing earlier than respondents with shorter distances, therefore, it is possible that such respondents would be unlikely to choose an earlier departure time because of their usual early departure.

* An examination of the distribution of departure times in the data set showed that the mean departure time for the data set was 07:46 with a standard deviation of 34 minutes. The 07:12 departure time was chosen because it was one standard deviation away from the mean.

Table 2 Models of departure time choice

Variables		Model DP1	Model DP2	Model DP3
TOLL (ED)		-1.048 (-11.8)	-1.025 (-10.8)	-1.060 (-10.7)
DEP (ED)		-.03675 (-2.8)	-.03641 (-2.7)	-.04316 (-3.1)
TIME (ED)		-.1086 (-2.8)	-.1072 (-2.7)	-.1178 (-2.9)
TOLL (SD)		-.8930 (-10.7)	-1.031 (-6.9)	-1.089 (-7.1)
TIME (SD)		-.1343 (-3.5)	-.1375 (-3.5)	-.1469 (-3.7)
TOLL (LD)		-.8866 (-10.4)	-.8971 (-9.8)	-.9556 (-10.0)
DEP (LD)		-.03347 (-2.5)	-.03765 (-2.6)	-.03421 (-2.4)
TIME (LD)		-.1287 (-3.3)	-.1297 (-3.3)	-.1378 (-3.4)
DISTANCE (ED)		-.05912 (-3.4)	-.06150 (-3.5)	-.05420 (-3.0)
DEP712 (ED)		1.361 (4.0)	1.447 (4.1)	1.756 (4.6)
CARDELAY (LD)		1.237 (4.5)	1.153 (4.1)	1.263 (4.3)
SINGLE (ED)		-1.223 (-4.2)	-1.243 (-4.2)	-2.238 (-6.0)
SENIORMGM (LD)		1.297 (3.1)	1.134 (2.6)	1.011 (2.3)
WILLPAY (ED)		.4711 (3.4)	.4938 (3.5)	.5430 (3.6)
SCHD (ED)		-.02853 (-5.8)	-.02919 (-5.8)	-.03008 (-5.8)
ARRIVAL (LD)		-.2419 (-2.7)	-.2723 (-2.4)	-.2894 (-2.4)
Constant (ED)		-	-1.738 (-2.1)	-1.229 (-1.4)
Constant (LD)		-	-2.244 (-2.5)	-3.209 (-3.1)
Availability coefficients				
(i) Single coefficients:				
ED alternative		-	.2416 (2.4)	-
LD alternative		-	.4615 (3.9)	-
(ii) A function:				
ED alternative	**START30E**	-	-	.4018 (1.2)
	START30L	-	-	.2909 (0.9)
	CHADWRK	-	-	.7613 (2.5)
	ACTSBEF	-	-	.2230 (0.6)
	INCBLAV	-	-	-1.238 (-3.1)
LD alternative	**START30E**	-	-	.3029 (0.9)
	START30L	-	-	.4931 (1.5)
	CHADWRK	-	-	.2387 (0.8)
	ACTSBEF	-	-	1.133 (2.7)
	INCBLAV	-	-	1.029 (2.2)
$\rho^2(0)$		.3244	.3374	.3673
$\rho^2(c)$		.3190	.3320	.3622
Final likelihood		-469.0914	-460.0876	-439.3171
n		632	632	632

Car users who experience delays at least once a week that result in them being at least 15 minutes late for work (CARDELAY) have, *ceteris paribus*, a higher probability of switching to a later departure time. Analysis of the choice data set reveals that a high percentage of respondents in this category can start work earlier (78%), start work later (82%) and had household incomes of more than £40,000 (82%). Thus, it appears that these respondents had the flexibility to choose later departure times rather than earlier or same as usual departures.

All else being equal, single persons (SINGLE) are less likely to switch to an earlier departure time. They may be willing to pay the toll rather than depart earlier than usual. Or, without the constraints of other household members an individual in a single person household will be in a better position to choose different departures times than individuals in households of more than one person (e.g. households with dependent children) and thus would choose the later rather than the earlier alternative.

The practical significance of the results presented is that there is evidence that a variable congestion charging scheme will result in switches in departure time to work, thus achieving a flattening in the peak period as travellers switch to earlier or later than usual departure times to work.

However, in certain cases departure time alternatives may not be available for some individuals because of their work schedules, and other commitments. This would limit their choices and ability to switch from one departure time to another. In the next section the availability of departure times defined by an individual's level of flexibility is discussed.

4. Investigation of departure time choice flexibility

The availability of alternative departure times to any individual is influenced by factors, which affect her flexibility such as dependent children and other commitments. Moreover, flexible working hours which have been increasingly adopted and promoted in a larger number of work places, will influence choice of departure time and hence, the availability of the alternative departure times.

In general it seems that individuals with lower levels of flexibility are restricted to their usual departure time alternative or choose to arrive at work early. Later departure time on the other hand will only be available to those with the highest levels of flexibility (in terms of work and other commitments).

Table 3 shows the distribution of departure time choices and the factors that affect flexibility. From the table it can be seen that of the respondents who could not start work earlier than usual, 40% of them chose their usual departure time, while only 32% of respondents who could start earlier chose this option. Similarly, almost 42% of respondents who could not start work later than usual chose their usual departure time. In contrast, only 32% of respondents who could start work later chose this alternative.

On the other hand, respondents who are more flexible are observed to be able to choose the early departure alternative over the same as usual alternative. For example, from

Table 3 it can be observed that more respondents without dependent children (or with dependent children and an adult at home) chose the earlier alternative (40.6%) rather than the same as usual alternative (32.1%). Likewise, more respondents with the ability to start work later than usual chose the earlier alternative (38.6%) rather than the same as usual alternative (29.8%).

In general, individuals who choose the later alternative tend to have more flexibility. For example, only 15% of respondents with below average household incomes chose the later departure time alternative compared to 30% with higher incomes. Similarly, almost 20% of respondents who could not start work earlier than usual chose the later alternative compared with 31% who could start earlier. Furthermore, only 15% of respondents with regular activities chose the later alternative compared to almost 30% with no such activities. These evidences suggest that individuals who choose the later alternatives tend to have the highest flexibility.

From the above discussion it seems that the same as usual alternative is the most available alternative, followed then by the earlier alternative and finally by the later than usual alternative. Moreover, these results show that that availability to an individual of alternative departure times depends on the individual's level of flexibility. In the following section levels of flexibility are defined based on the factors discussed in this section.

Table 3 Flexibility related factors and choice of departure time alternative

Choice of alternative	**Household income below the Scottish average**		**Ability to start work at least 30 minutes earlier**		**Ability to start work at least 30 minutes later**		**Dependent children and all adults working**		**Regular Activities before work**	
	Yes	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**
ED	48.7%	37.2%	37.7%	41.0%	38.6%	38.7%	32.9%	40.6%	41.8%	38.1%
SD	35.9%	33.2%	31.3%	39.3%	29.8%	41.7%	37.9%	32.1%	42.9%	32.0%
LD	15.4%	29.6%	31.1%	19.7%	31.6%	19.6%	29.2%	27.4%	15.4%	29.9%
n	78	554	454	178	433	199	161	471	91	541

4.1. Defining flexibility

As discussed in the previous section, more factors than just those related to the work schedule can affect any individual's flexibility in choosing departure times. Moreover, the availability of departure time alternatives will depend on the individual's levels of flexibility. These factors could include socio-economic, work schedule or activities/commitments regularly carried out by an individual, or indeed any other factor that is deemed appropriate to define flexibility. In fact, Small (1982) indicated that scheduling flexibility was determined by factors related to family status, mode choice, occupation and work schedule flexibility. He found that the coefficients of his departure time models were dependent on these factors. In this work we define explicitly a function of flexibility to determine the availability of departure time alternatives as will be explained in section 5.

In this study, five factors have been defined as affecting an individual's level of flexibility, these are:

1. x_1: this represents an individual's ability to start work at least 30 minutes earlier than official work start time (or usual start time if on flexitime or no fixed hours). It takes a value of 1 if a respondent answers yes, and 0 otherwise (which implies no flexibility of departure time switch).
2. x_2: this represents an individual's ability to start work at least 30 minutes later than official work start time (or usual start time if on flexitime or no fixed hours). It takes a value of 1 if a respondent answers yes, and 0 otherwise.
3. x_3: this represents whether or not an individual has dependent children with all adults in the household working. It takes a value of 0 if a respondent answers yes, and 1 otherwise.
4. x_4: this represents whether or not an individual regularly carries out activities before work (excluding dropping off children). It takes a value of 0 if a respondent answers yes, and 1 otherwise.
5. x_5: this represents whether or not an individual has a household income below the Scottish average. It takes a value of 0 if a respondent answers yes, and 1 otherwise.

Each of these factors listed, which have been treated as dummy variables, were then combined to define levels of flexibility using a simple scoring approach as set out in Figure 3.

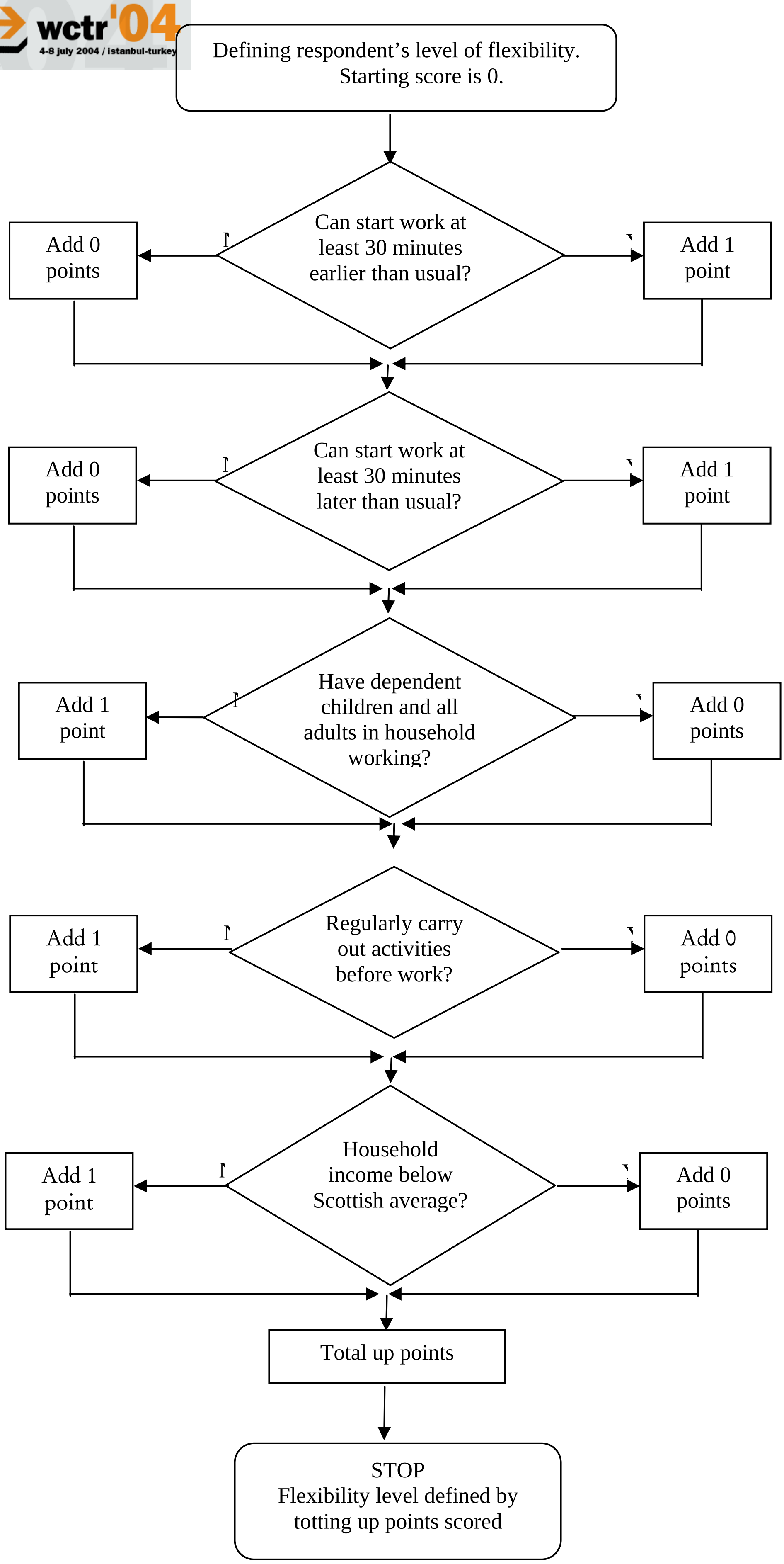

Figure 3: A flow chart to define a respondent’s flexibility level

Figure 4 shows the trend in departure time choice with the calculated values of the flexibility score. From the graph it appears that as flexibility increases, the number of respondents choosing the earlier or same as usual departure time alternative decreases while the numbers choosing the later than usual departure time alternative increases. Therefore an individual's level of flexibility can be used to define the availability of departure time alternatives and that the later departure time requires the most flexibility. As stated previously, a simple scoring approach has been used in this study, however, other scoring approaches could be adopted including the weighting of certain variables.

In this work we assume that individuals with the highest levels of flexibility have a choice of the three departure time alternatives (ED, SD, and LD), while those with lower levels of flexibility are constrained in their choices, subject to their level of flexibility. Those who are non-flexible are captive to their usual departure time alternative. Therefore, departure time choice sets can be defined in descending order as:

1. {SD, ED, and LD alternatives} highest levels of flexibility
2. {SD and ED alternatives} lower levels of flexibility
3. {SD alternative} for non flexible individuals, i.e. captive to their usual departure time

There is a large amount of research on the definition and modelling of availability of various choice alternatives mostly for the case of mode choice. However, the authors are not aware of any similar work in the case of departure time modelling. In this work we model the availability of departure time alternatives as a function of the individual's level of flexibility in two cases. Firstly, single coefficients for the flexibility function are calibrated and secondly, a function of the flexibility parameters is being used as presented in section 5.

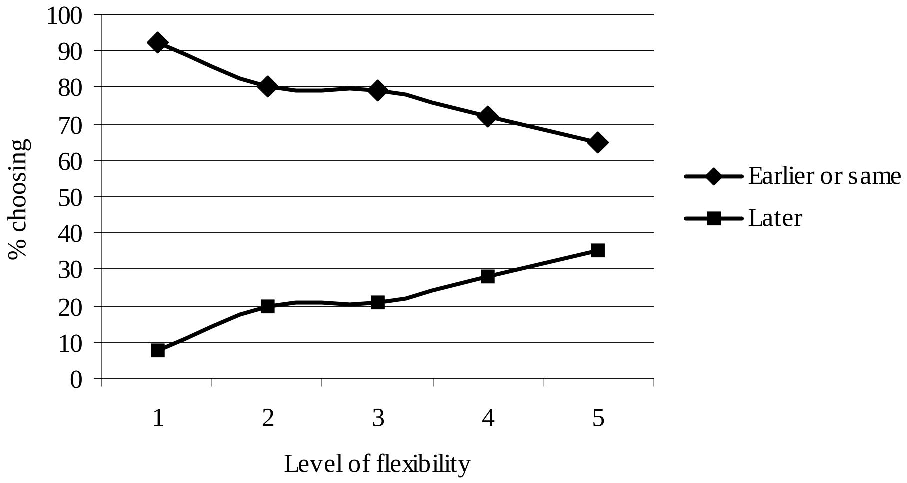

Figure 4 Choice of departure time alternative against level of flexibility

5. Modelling departure time availability

In general, we can write that the probability of choosing any alternative *j* of a finite set of alternatives (*A*) from a choice set *C* (Manski, 1977) follows the following conditional probabilities:

$$P_j = \sum_{C \in T_j} P(C).P(j \mid C) \quad (3)$$

where C is a choice set and T_j is the set of choice sets containing alternative j. This decomposition can be used to formulate models, which explicitly consider all the forms of full and partial captivity.

Assuming that an individual chooses alternative j, then the number of feasible choice sets containing that specific alternative is given as:

$$T_j = (j, ..., A) \quad (4)$$

where T has a $2^{(J-1)}$ elements and A defines the full choice set with all alternatives, 1,...,J. If T_j is very large, considering all the available choice sets is computationally difficult. This concept has been adopted previously to restrict the number of choice sets considered in any specific context and to define various discrete choice models, mainly for mode choice (for more discussions see for example, Saleh & Bell, 1998; Gaudry & Dagenais, 1979; and Swait & Ben-Akiva, 1987a, 1987b).

In this work the availability and the choice of departure time alternative i are jointly modelled as:

$$P(i) = P(a_i).P(i \mid a_i) \quad (5)$$

where $P(a_i)$ is the probability of availability of alternative i in the choice set, defined here as an exponential function (however other forms are possible), and $P(i \mid a_i)$ is the probability of choosing alternative i given that it is available.

Note that when $P(a_i) = 0$, (i.e. all the flexibility attributes equal zero) that means that alternative i is not available for that individual and therefore $P(i) = 0$. Whereas, should the attributes of the flexibility function be included in the utility function of that alternative, the probability of choosing alternative i would only be reduced. In the following sections the modelling results are presented where $P(a_i)$ is defined as a function of the flexibility attributes of the individuals. Firstly, as single coefficients (section 5.1), and secondly as a parameterised function of the attributes of the individual's flexibility (section 5.2)

5.1. Modelling the availability of departure times as single coefficients

In this case the probability of availability of any departure time alternative $P(a_i)$ can be expressed as:

$$P(a_i) = e^{\alpha_i \sum x_k} \quad (6)$$

where i is any departure time alternative, x_k are attributes of the individual's level of flexibility (socio-economic, work and other commitments) and α_i are coefficients to be estimated. The probability of choice of any departure time is as defined in equation 5.

The results of the departure time model (Model DP2) including the coefficients of the flexibility function are presented in Table 2. Two coefficients were specified in the utility functions of two of the three departure time alternatives (earlier and later alternatives). All of the coefficients for model DP2 are statistically significant (including the two flexibility coefficients) at the 5% significance level. Both of the flexibility coefficients have the expected positive sign. Thus, respondents with more flexibility will have more alternatives available to them and are thus more likely to choose either the earlier or later departure time alternatives. Furthermore, the LD alternative (with its higher positive value for the availability coefficient) is more likely to be selected than the ED alternative.

This model also includes two alternative specific constants, which were specified in the ED and SD alternatives. Both of these coefficients are negative. Thus, all else being equal, the LD alternative (with its negative value for the constant) is less likely to be selected relative to the SD alternative. The ED alternative with its negative constant is less likely to be selected relative to the SD alternative. Furthermore, the LD alternative (with its higher negative value for the constant) is less likely to be selected than the ED alternative as these are work trips and people tend to prefer not to be late for work. Unlike model DP1, in this model the greatest disutility for tolls is shown for the SD alternative. This may because of higher tolls for travel at the same time as usual.

Model DP2 performs better than the base model DP1 (which excludes the flexibility coefficients that define availability), showing an improvement in the ρ^2(c) from 0.3190 to 0.3320.

5.2. Modelling the availability of departure time as a function

In this case the probability of availability of any departure time alternative $P(a_i)$ can be expressed as a parameterised function of the attributes of the individuals' flexibility function:

$$P(a_i) = e^{\sum \alpha_{ik} x_k} \qquad (7)$$

where i is any departure time alternative, x_k are the parameters that define an individual's level of flexibility (socio-economic, work and other commitments) and α_{ik} are parameterised coefficients of flexibility to be estimated. Again, the probability of choice of any departure time is defined as in equation 5.

Model DP3 shows the results of this model. All of the coefficients have their anticipated signs and most of the coefficients are statistically significant at the 5% significance level. The toll coefficients follow the same pattern as model DP2, with the highest disutility associated with tolls for the SD alternative. The departure time coefficients follow the same pattern as the base model (Model DP1), with the highest disutility for the ED alternative. And like both of the previous models, there is less preference for increases in travel time for the SD alternative.

Model DP3 performs better than either model DP1 (which excludes the flexibility coefficients that define availability) and model DP2 which has single coefficients of flexibility. The ρ^2(c) for model DP3 is 0.3622 compared to 0.3320 for model DP2 and 0.3190 for model DP1.

6. Behavioural implications, discussion, and conclusions

There are circumstances where an individual's choice of departure time is affected by factors such as work schedule flexibility and other personal constraints such as activities before work and dependent children. Availability of departure time alternatives have been defined and modelled as a function of levels of flexibility for each individual. The factors affecting flexibility have been defined as: the ability to start work earlier and/or later than usual, the presence or absence of dependent children with all adults in the household working, the presence or absence of regular activities before work, and the income of the individual. The flexibility coefficients are not estimated as part of the utility function but as a separate function. Ignoring these flexibility related factors or only including them in the utility function would result in mis-specification of the results, and perhaps over or underestimation of the prediction of departure time options.

The calibrated model, which includes flexibility coefficients as defined by levels of flexibility (model DP2) performs better than the model without these coefficients (DP1). Coefficient estimates for model DP2 are statistically significant and have signs consistent with expectations. However, model DP3 with includes a flexibility function to define availability of departure time alternatives performs better than the other two models.

To more accurately assess the implications of the coefficient estimates, elasticities were calculated (for model DP3). The earlier, same as usual and later departure time choices with respect to toll are elastic with elasticities of 1.2, 1.9 and 1.4 respectively. Furthermore, the elasticity of departure time choice (for same as usual departure) with respect to toll is higher than for either earlier or later departure time choice. Thus, a 10% increase in the toll applied to departures at the same time as usual, will all else equal, result in 19% decrease in the probability of the same as usual departure time being chosen. This finding is encouraging as one expects respondents to look to alternative departure times in an attempt to avoid paying the toll or to reduce the amount of toll that they would pay. This shows a potential reduction in the peak of departure times as a result of introducing variable congestion charges.

From the coefficient estimates of model DP3 it seems that the trade-off money value for toll and departure time is slightly higher for earlier than for later departure times (£2.44 per hour and £2.15 per hour respectively). In other words, users are willing to pay slightly more to save departure time at an earlier time than for departure time at a later time. This implies higher values of earlier departure time than of later departure times. This makes intuitive sense, if respondents are going to pay a toll to depart earlier than usual, then the preference is that the number of minutes earlier that they must depart should not be too great. Whereas, although respondents are willing to pay to save having to depart too much later, they are not willing to pay quite as much, perhaps because departing later is not as much of an inconvenience as departing earlier (e.g. having to get out of bed earlier, leave the home earlier, arrive at work before other colleagues etc.).

Similarly, the values of time estimated from model DP3 imply that a sampled individual departing earlier than usual is willing to pay quite a lot less (£6.67/hr) to save one hour of travel time than for departing at the same time as usual (£8.65/hr) or departing later than usual (£8.09/hr). This implies that the highest values of time are for departures at the same time as usual and lowest values for departures earlier than usual. Again, this makes intuitive sense, as savings in travel time associated with an earlier departure time may not be as important because earlier departure will result in earlier arrival time at work (particularly with the addition of travel time saving associated with congestion charges).

In conclusion, a congestion charging scheme has the potential to significantly impact on travel behaviour, and in particular on departure time switch if the scheme adopted is based on a variable charging structure. If a scheme is introduced with variable charges applied during the day, shifting peaks or peak spreading will be an objective of the scheme. It is therefore imperative that departure time switch is addressed in the analysis of potential impacts of a charging scheme. Furthermore, flexible working hours and flexible working patterns (e.g. working from home), and indeed other workplace policies such as childcare facilities should be considered in conjunction with a variable based congestion charging scheme so that the constraints on departure time choice can be reduced to allow more people to choose alternative departure times to work.

The results of the models presented in this paper show a potential improvement in the performance of the model when levels of individual's flexibility are used to define availability of departure time alternatives. Thus, further research into the affects of flexibility levels on availability of departure times is warranted.

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