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The Optimal Choice of Commuting Speed: Consequences for Commuting Time, Distance and Costs

Jos Van Ommeren and Joyce Dargay

Address for correspondence: Jos Van Ommeren, Free University, FEWEB, De Boelelaan, 1081 HV Amsterdam (jommeren@feweb.vu.nl). Joyce Dargay, Transport Studies Unit, Oxford University Centre for the Environment, Dyson Perrins Building, South Parks Road, Oxford OX1 3QY (jdargay@ouce.ox.ac.uk). Support from the Economic and Social Research Council of the UK is gratefully acknowledged. We would like to thank the editor and anonymous referee for useful comments and Marcel Hoogzaad, Jolanda van Velsen and Mark Hanly for valuable assistance.

Abstract

In this paper, we derive a structural model for commuting speed. We presume that commuting speed is chosen to minimise commuting costs, which encompass both monetary and time costs. At faster speed levels, the monetary costs increase, but the time costs fall. Using data from Great Britain, we demonstrate that the income elasticity of commuting speed is approximately 0.13. The ratio of variable monetary costs to travel time costs is estimated to be about 0.14. An implication of this is that as incomes rise commuters choose faster modes, despite their higher monetary costs. This has been an important factor in the growth of commuting by car in the past decades (for example, during the 90s the percentage of work trips made by car in Britain increased from 65 per cent to 70 per cent) and is anticipated to be relevant in the next decades for developing countries such as China and India. With increasing congestion, the time-advantage of car travel will decline, but unless faster public transport modes are available, there will be little incentive to switch to public transport (unless the monetary costs decline substantially in relation to car travel).

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1.0 Introduction

Since the pioneering work of McFadden (1974), a large number of studies on the choice of travel mode have appeared in the transport economics literature. According to these studies, time and monetary costs are the structural components of the travel mode choice, although other components (convenience and so on) certainly have a strong influence. One finding of this travel mode literature is that income is among the relevant explanatory variables determining mode choice (Train, 1980; Kitamura, 1989; Jara Diaz and Videla, 1989; Dargay and Hanly, 2004).[1] Low-income travellers apparently choose a lower speed level to economise on monetary costs (Jara Diaz and Videla, 1989).[2] The implication is that the value of time depends positively on income (Wardman, 2001) and that the chosen speed level depends positively on income. One aim of this paper is to model this relationship more explicitly.

In another strand of transport economics literature, the focus is on the cost of transport for the user as an element in the determination of demand (Quinet and Vickerman, 2004). For example, Littman (1999) shows in an analysis of automobile costs in a Canadian urban context, that the time costs are about twice the variable monetary vehicle costs. The current study also contributes to this literature, by showing that information on the travellers' time and monetary costs can be derived given observations of their chosen speed level and income.

We derive a structural model for commuting speed and identify the relationship between monetary costs and speed level given reduced form estimates of the income elasticity of the speed level.[3] The theoretical analysis demonstrates that given an income elasticity of 0.5, the monetary costs are a linear function of speed, but for lower elasticities, the monetary costs are a convex function of speed.[4] When the income elasticity is (close to) zero, then the commuter is essentially restricted in the choice of the optimal speed level. We also demonstrate that the ratio of the variable monetary costs to time travel costs, which is optimally chosen by the commuter by choosing the optimal speed, depends on how the monetary costs vary with speed. It appears that this ratio depends negatively on the marginal monetary costs of speed. Further, it appears that when the monetary

[1] In stated choice models, the main consequence is that income is interacted with travel cost, and that for lower income travellers, cost has a more negative effect.

[2] This finding supports the literature on the trends in commuting distance, time and speeds travelled, which essentially demonstrates that average commuting speed has increased substantially over the last couple of decades during which we have observed strong GDP growths.

[3] Given information on how the monetary costs of commuting depend on the speed level (see Rouwendal, 1996), the value of time can be used to predict the chosen speed level.

[4] In case of an income elasticity that exceeds 0.5, the monetary costs are a concave function of speed.

costs are a linear function of speed, the variable monetary costs are equal to the travel time costs when the speed is optimally chosen. In contrast, when the monetary costs are a convex (concave) function of speed, the variable monetary costs are less (more) than the time travel costs. We demonstrate on the basis of British data that the income elasticity of speed is close to 0.13, implying that the monetary costs are a convex function of speed, and that the variable monetary costs are less than the time travel costs. We find that the ratio of monetary costs to time travel costs is about 0.14 (with a standard error of 0.06).

We emphasise that our analysis focuses on commuters, and not on travellers in general, for a number of reasons. First, value of time estimates vary widely among different travel purposes (Small, 1992). Commuters are a relatively homogeneous group of travellers for which assumptions on the value of time make more sense. Second, in the case of commuting, the commuting distance can be instrumented avoiding problems with the endogeneity of distance to speed, whereas this may be more difficult for other travel purposes.

The outline of the paper is as follows. In Section 2, we derive a structural model for speed and show how one can estimate and identify the parameters of interest based on reduced form estimates. In Section 3, the empirical results are presented, and in Section 4 the interpretation of the estimates in terms of the structural model are discussed. Section 5 concludes.

2.0 The Optimal Speed Model

2.1 The structural model

In the current paper, we focus on employed individuals who earn an hourly wage w and who aim to minimise the commuting costs, conditional on the commuting distance. Workers' commuting costs t are generally thought to consist of two main components — monetary commuting costs t_m and travel time costs t_c. Workers can influence both commuting costs components by choosing the desired travel speed s. So, the commuting costs are determined by the travel speed s conditional on the commuting distance d. The choice of the travel speed determines the monetary and travel time costs. Note that the commuting costs include a fixed component, which does not depend on the chosen speed level.[5] As the size of this

[5]The fixed component can be defined as the minimum monetary costs to travel a certain distance using any travel mode within the choice set. For longer distances, the choice set does not include walking and bicycling. Clearly, the fixed component is increasing in distance.

component does not influence the chosen level of the speed, we will only focus on *variable* commuting costs.

We assume that the monetary costs t_m depend positively on the travel speed, but also depend on spatial characteristics[6] X and distance d.[7] It is assumed that t_m is a continuous function of speed s.[8] We will assume $t_m = \kappa(X, d)s^{\alpha_s}d$, hence t_m is parameterised as a power function of s ($\alpha_s > 0; \kappa(X, d) > 0$), so t_m is assumed to be increasing in the speed level and we allow for interactive effects between the speed level s, X and d. The parameter α_s may be interpreted as the speed elasticity of the monetary costs (per distance). This interactive effect may exist, for example, because at long distances, the marginal monetary costs with respect to speed may be less than at short distances. The hourly time travel costs are assumed to be proportional to the hourly wage w, so $t_c = \psi w h_c$, where $\psi > 0$ and ψw is the value of time, and h_c is the commuting time.[9] It may be the case that ψ is a function of individual characteristics Z (but not of spatial characteristics), so $\psi = \psi(Z)$. We will assume that:

$$\psi(Z) = \alpha_{z0} \exp^{\alpha_z . Z}, \tag{1}$$

where α_{z0} denotes a constant.

[6] We assume that monetary costs do not depend on the socio-demographic characteristics of the individual or on income. This, however, may not always be valid. One example of the former could be that maintenance costs may be lower for men than for women, as men are typically more likely to undertake car repairs themselves. An example of the dependency on income could be that higher income individuals have newer and more expensive cars for their reliability, comfort and status, rather than (or in addition to) their speed.

[7] We may ignore the situation where the commuting costs depend negatively on speed, because this would imply that the maximum possible speed would always be chosen.

[8] The standard way to study modal choice is to apply discrete choice methods. As one proceeds from one mode to the other (for example, from bicycle to bus), a discrete jump takes place in terms of both speed and monetary costs. In the present context we model these costs as a continuous function of speed. The assumption that t_m is continuous may be less restrictive than often thought for a number of reasons. First, commuters may choose from a number of mode choices, which reflect different speed levels. Second, many commuters combine several private and public transport modes for a trip (such as walking and underground; train and taxi) or use a combination of modes for different trips (Van Exel and Rietveld, 2004). Third, car drivers influence the speed level by changing departure time to and from work. Fourth, given the choice of the car, the monetary costs increase with speed in a continuous way through fuel costs, accident costs and fines which all depend on the speed level (Rouwendal, 1996; Rienstra and Rietveld, 1996; Verhoef and Rouwendal, 2001; Gander, 1985; Rotemberg, 1985).

[9] Note that this functional form implies that the value of travel time elasticity is equal to one. Empirical studies suggest that this elasticity is less than one although the elasticity for commuting is usually thought to be much higher than for non-commuting time (Small *et al.*, 1999; Mackie *et al.*, 2003; AHCG, 1999). A recent study by Fosgerau (2005b), however, finds a unit elasticity and suggests that previous studies may be underestimates. The consequences of the unit assumption will be discussed at the end of Section 4.

Given the relationship between commuting time, speed and distance, total variable commuting costs t can be written as:

$$t = \left[\frac{\psi(Z)w}{s} + \kappa(X, d)s^{\alpha_s} \right] d, \tag{2}$$

where the first term between brackets denotes the travel time costs per distance unit and the second term denotes the monetary costs per distance unit. Conditional on the commuting distance and the wage, the employee chooses the optimal speed s^* by minimising total commuting costs. The first-order condition ($\partial t/\partial s^* = 0$) implies then that:[10]

$$\frac{t_m}{t_c} = \frac{1}{\alpha_s}, \quad \text{if } s = s^*. \tag{3}$$

Hence, given the optimal speed level, the ratio of the (variable) monetary costs to the time costs is equal to the inverse of the speed elasticity of the monetary costs. Note that this ratio does *not* depend on any other variable such as the speed level or the wage, because the speed level, and therefore, this ratio are optimally chosen.

In the special case that the monetary costs are a linear function of the speed level, then $\alpha_s = 1$. This implies that in this special case $t_m = t_c$, so the optimal speed is chosen such that the time travel costs are equal to the variable monetary travel costs. Now suppose that the monetary costs are a convex (concave) function of speed, conditional on distance, so $\alpha_s > 1 (\alpha_s < 1)$. In this case, the variable monetary costs exceed (are less than) the time costs. In the current paper, we will estimate α_s, which enables us to estimate the ratio of monetary costs to time costs.

To derive how the optimally chosen speed depends on Z, X, d and w, we proceed by presuming a certain functional form for $\kappa(X, d)$. We will suppose that:

$$\kappa(X, d) = \exp^{\alpha_0 + \alpha_x X + \alpha_d \log d}. \tag{4}$$

So the parameter α_d is the distance elasticity of the monetary costs per distance, and $\alpha_d + 1$ is the distance elasticity of the monetary costs.[11] Given (3), $\kappa(X, d)s^{\alpha_s} = (1/\alpha_s)\psi(Z)w/s$ and using (1) and (4), the optimally

[10] The assumption that α_s exceeds zero guarantees that the second-order condition of the worker's minimisation problem is fulfilled in the optimum, which guarantees a finite speed solution.

[11] It may be thought that α_d must exceed -1, because the total monetary costs must be an increasing function of distance d. However, α_d may be less than -1, because total monetary costs consist of a fixed component, which does not depend on speed, and a variable component. In case that the fixed monetary costs increase as a function of distance, then the variable monetary costs may decrease in distance, so α_d may be less than -1.

chosen speed level s^* can be written as:

$$\log s^* = \frac{[\log \alpha_{z0} + \alpha_z Z - \alpha_0 + \log w - \alpha_x X - \alpha_d \log d - \log \alpha_s]}{1 + \alpha_s}. \tag{5}$$

One of the main implications of (5) is that the optimal speed depends positively on the wage (since $\alpha_s > 0$).[12]

2.2 The reduced form model

In order to estimate the structural parameters of (5), we estimate a reduced form model and to do so we also introduce unobserved heterogeneity. It is natural to assume that individuals deviate from each other in unobserved ways not taken into account by equation (5). This implies that:

$$\log s^* = \beta_0 + \beta_x X + \beta_z Z + \beta_w \log w + \beta_d \log d + u, \tag{6}$$

where β are reduced form parameters and u is random error.

2.2.1 Identification

Identification of the structural parameters is straightforward. Given (5) and (6), it appears that:

$$\beta_z = \alpha_z/(1 + \alpha_s), \tag{7}$$

$$\beta_x = -\alpha_x/(1 + \alpha_s), \tag{8}$$

$$\beta_w = 1/(1 + \alpha_s), \tag{9}$$

$$\beta_d = -\alpha_d/(1 + \alpha_s), \tag{10}$$

It can be easily seen that β_w is the income elasticity of speed and because $\alpha_s > 0$, it follows that $\beta_w < 1$. In the case where the monetary costs are a linear function of speed, so $\alpha_s = 1$, then $\beta_w = 1/2$. In the case where the monetary costs are a convex function ($\alpha_s > 1$), then $0 < \beta_w < 0.5$. Only when α_s goes to infinity, so the commuters are fully constrained in their choice of speed, then $\beta_w = 0$.[13] In the case of a concave function, $\beta_w > 0.5$. The reduced form parameters can be estimated by means of a regression of the logarithm of the speed level s on the logarithm of the wage w, the characteristics X and Z and the logarithm of commuting

[12] In line with this statement there is some empirical evidence that given the choice of a car, those with high incomes travel faster (Rienstra and Rietveld, 1996; Fosgerau, 2005a). In Section 3, we will examine this statement more carefully.

[13] One may argue that congestion may fully constrain car drivers when the *whole* trip is congested *and* there are no alternatives. For short distances, it is more likely that the *whole* trip is congested (such as in the centre of London), but in this case alternative modes are often available (for example, walking, underground and so on).

distance d.[14] Given the reduced form estimates of β_z, β_x, β_w and β_d, the 'structural' parameters α_z, α_d, α_s and α_x are identified when Z and X do not include the same variables.[15] Clearly:

$$\alpha_z = \beta_z/\beta_w, \tag{11}$$

$$\alpha_d = -\beta_d/\beta_w, \tag{12}$$

$$\alpha_x = -\beta_x/\beta_w, \tag{13}$$

$$\alpha_s = 1/\beta_w - 1. \tag{14}$$

The above results make sense.[16] For example, α_z can be interpreted as the effect of Z on (the logarithm of) the value of time (see (1)), which is proportional to the wage. Hence, the speed level will be optimally chosen such that α_z is equal to the ratio of the marginal effect of Z on speed to the marginal effect of (the logarithm of) the wage on speed (see (11)).

2.2.2 Comparative statics

Given the reduced form parameters, one can easily estimate the effects of Z, X, d and w on the monetary costs, presuming that individuals have chosen the optimal commuting speed. Note that $t_m = t_c/\alpha_s$, so $\log t_m = \log t_c - \log \alpha_s$. It follows that:

$$\begin{aligned} \log t_m = {} & (1/\beta_w - 1)\beta_z Z - \beta_0 - \beta_x X + [1 - \beta_w] \log w \\ & + [1 - \beta_d] \log d - \log(-1 + 1/\beta_w) - u, \end{aligned} \tag{15}$$

so:

$$\partial \log t_m / \partial \log w = 1 - \beta_w, \tag{16}$$

$$\partial \log t_m / \partial X = -\beta_x, \tag{17}$$

$$\partial \log t_m / \partial \log d = 1 - \beta_d, \tag{18}$$

$$\partial \log t_m / \partial Z = (1/\beta_w - 1)\beta_z. \tag{19}$$

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[14] As we will argue later on, the endogeneity of distance should be taken into account.

[15] As noted earlier, there may be cases where t_m includes income. However, we assume these to be of minor importance and thus omit them. For example, when monetary costs include schedule delay costs, then it may be argued that the wage enters t_m because wage may affect schedule delay costs. There is some evidence that for this reason t_m is a negative function of wage w (Emmerink and Van Beek, 1997). We do not explicitly allow for that, so our estimates of α_s may be slightly biased upwards.

[16] For environmental characteristics (such as the urban density), it is implausible that they affect *directly* the monetary value of time, so they are not included in Z. For some individual characteristics one may argue that these should be included in both Z and X, because they may influence the value of time but also the monetary variable costs, so for these variables the structural parameters are not identified. Suppose that the variable XZ is in X and Z. In this case, $\beta_{xz} = (\alpha_z - \alpha_x)/(1 + \alpha_s)$.

Hence, given the reduced form estimates, we are able to identify the effects of X, Z, d and w on (the logarithm of) the monetary costs. For example, the reduced form estimates β_x can be interpreted as minus the marginal effect of X on $\log t_m$ (see (17)). The marginal effect of Z has the same sign as β_z, because $1/\beta_w - 1 = \alpha_s > 0$. Recall that we have shown that if the commuter chooses the optimal speed, then $t_c = \alpha_s t_m$ (see (3)), so it follows that $t = (\alpha_s + 1)t_m$ and thus $\log t = \log(1 + \alpha_s) + \log t_m$. Consequently, the (partial) effect of any exogenous variable on the logarithm of the commuting costs $\log t$ is equal to the (partial) effect on the logarithm of the monetary commuting costs $\log t_m$.

Note that $\partial t_m/\partial s = t'_m = \alpha_s t_m/s$, hence:

$$\log t'_m = \log \alpha_{z0} + \beta_z(1/\beta_w - 2)Z + \log w - 2[\beta_0 + \beta_x X + \beta_w \log w + [\beta_d - \tfrac{1}{2}] \log d + u], \tag{20}$$

so:

$$\partial \log t'_m/\partial \log w = 1 - 2\beta_w, \tag{21}$$

$$\partial \log t'_m/\partial X = -2\beta_x, \tag{22}$$

$$\partial \log t'_m/\partial \log d = 1 - 2\beta_d, \tag{23}$$

$$\partial \log t'_m/\partial Z = (1/\beta_w - 2)\beta_z. \tag{24}$$

Hence, we are able to calculate how the optimally chosen marginal monetary costs t'_m depend on w, Z, X and d.[17] In Table 1, we have summarised the effects.

It appears from Table 1 that the reduced form estimates (β_z, β_x, β_w and β_d) can be readily interpreted. For example, the effect of a variable X_i on $\log s$ can be interpreted as (the negative of) the effect of this variable X_i on the logarithm of the commuting costs, $\log t$. The implication is, of course, that if in an area the average speed is, about 10 per cent lower, for example, due to speed restrictions which require commuters to drive at 45 mph instead of 50 mph, then the implied additional commuting costs are equal to 10 per cent when the speed is optimally chosen. However if commuters in the area with the speed restrictions of 45 mph drive at 50 mph, then the implied additional monetary costs are equal to $\alpha_x = -\beta_x(1 + \alpha_s)$ (see the last column of Table 1). Speed restrictions imply a convex monetary costs function (which may be presumed to be a continuous function of speed, because the probability of being fined is a continuous function of speed), so $\alpha_s > 1$, so α_x is at least twice β_x. For example, when $\alpha_s = 5$, the implied monetary costs of driving 55 mph would be 50 per cent higher than when driving 50 mph.

[17] Recall that $\partial t/\partial s^* = 0$, so $t' = 0$ and $t'_m = -t'_c$.

Table 1
Comparative Statics: Marginal Effects

	(1) $\log s$	(2) $\log t$	(3) $\log t'_m$	(4) $\log t_m \vert s$	(5) $\log t_c \vert s$
Z	β_z	$(1/\beta_w - 1)\beta_z$	$(1/\beta_w - 2)\beta_z$	–	α_z
X	β_x	$-\beta_x$	$-2\beta_x$	α_x	–
$\log w$	β_w	$1 - \beta_w$	$1 - 2\beta_w$	–	1
$\log d$	β_d	$1 - \beta_d$	$1 - 2\beta_d$	α_d	1

Notes: $\log t'_m = \partial \log t_m / \partial s$; $\log t$ and $\log t'_m$ are determined given the optimally chosen speed level. In the last two columns, the effect is reported on the monetary and time costs conditional on the speed level. When the X and Z variables are discrete dummy variables, then the effect of a variable with effect of size γ is equal to $\exp \gamma - 1$, which is approximately equal to γ when γ is small.

In the third column, the effect of characteristics on the marginal commuting costs with respect to speed can be found. The interesting hypotheses here are whether $1 - 2\beta_w = 0$, so $\beta_w = 0.5$, and whether $1 - 2\beta_d = 0$, so $\beta_d = 0.5$. In the case that $\beta_w = 0.5$, the implication is that the wage has no effect on the marginal monetary costs. Similarly, if $\beta_d = 0.5$, then the distance has no effect on the marginal monetary costs.

3.0 Empirical Results

3.1 The data

The empirical analysis involves estimating equation (6). This requires information on commuting speed, commuting time, the wage rate and other variables that influence choice of travel speed, preferably on the individual level. We use data from National Travel Surveys (NTS) for Great Britain. The NTS is based on a 7-day travel diary for a sample of private households and includes information on distance, time, purpose and mode for all trips made by each household member. It also includes data on a large number of socio-economic and demographic characteristics relating to the individuals and households.

Our analysis employs data for the six years 1989–1991 and 1999–2001. Using data for three consecutive years insures that the sample is representative of the British population and the two 3-year periods increases the variation in the variables, as well as providing the possibility of examining changes in behaviour over time. The analysis is based on individuals who report work trips by all modes on a given day.[18] Thus all stages of the

[18]Diary day 7 is chosen because walk trips of less than 1 mile are not included on the other days.

commuting journey, both to and from work, are included in the measures of commuting time, distance and speed. In our sample, the average commuting time per working day is 43 minutes (s.d. = 34), the average commuting distance is 15 miles (s.d. = 19) and the average commuting speed is 18 miles per hour (s.d. = 12).[19]

A most important explanatory variable in our model is the wage rate. Information on the hourly wage is not collected in the NTS, so the annual gross income of the individual is used instead.[20] Other explanatory variables included in the model relate to characteristics of the individual, the household to which they belong, and the area in which they live. Characteristics of the individual are gender, age, whether they are full- or part-time employed and whether they are employed or self-employed. The characteristics of the household include the number of adults in the household and whether or not there are children in the household. The location variables are the population density and the population of municipality where the individual resides. Apart from income and distance, all explanatory variables are binary variables equal to 1 if the condition holds, and zero otherwise. The estimation thus requires one variable in each group to be omitted and the coefficients of the remaining variables are interpreted in relation to the reference group. A dummy variable equal to one for the 1999–2001 data and zero for the 1989–1991 data is also included to allow for a difference in intercept over the 10-year period.[21]

3.2 The estimation procedure

In the theoretical analysis, it is assumed that the commuting distance is exogenously given. This assumption is unlikely to hold in the data we analyse. For example, it may be the case that some individuals may have a preference for a faster (or slower) travel mode (such as the car) for reasons unrelated to speed (such as convenience) and are therefore more likely to commute faster (or slower) than other individuals. Given higher speed levels, these individuals are more likely to accept longer distances *a priori*.

[19] The coefficient of variation (the standard deviation divided by the mean) for speed equals 0.66, for time equals 0.79 and for distance equals 1.26. Hence, the variation in the chosen speed level is relatively small compared to commuting time and particularly distance. This makes sense as those with a long commuting distance travel at higher speeds, explaining why the coefficient of variation of time is less than the coefficient of distance.

[20] Income is given in 20 income groups in the NTS. The individual's income is taken as the mid-point of the group, converted to year 2000 prices using the retail price index. Note that we use gross income instead of net income (after tax) as this variable was not available. The main consequence is that the standard estimates α_i are somewhat lower than reported here.

[21] The variables speed, income and distance enter the model in logarithmic form, so that the coefficients relating to income and distance are in elasticity form, which are constant by this specification.

A similar problem occurs when some individuals are more restricted in maximum speed levels than others. Individuals face different degrees of physical and legal constraints which affect the maximum costs of speed (for example, congestion, maximum speed restrictions).[22] If individuals are constrained at different levels, then it means that those who are able to travel at higher speeds without exceeding the maximum speed restriction may accept jobs at longer distances *ceteris paribus*. Further, it is difficult in the empirical analysis to control fully for the variation in the spatial environment (for example, supply of public transport, congestion, motorway accessibility, and so on) which may cause the commuting distance to become endogenous. If commuting distance is endogenous, it will be correlated with the error term so that the OLS estimates of (6) will not be consistent. Consistent estimates can be obtained by using an instrumental variables (IV) estimation procedure. As an instrument for commuting distance, we use the skill level of the job. The skill level should not influence the optimal speed conditional on income, but will influence the density of acceptable jobs, and therefore the commuting distance. It is generally true that jobs involving higher skill levels are more specialised and therefore less common, implying longer commuting distances (Rouwendal and Rietveld, 1994).

3.3 The reduced form estimates of speed

Both OLS and IV estimates are presented in Table 2, along with goodness-of-fit and test statistics. The Hausman Test for the exogeneity of the distance variable, shown at the bottom of the table, is 2.398, so that exogeneity cannot be rejected at the 0.10 probability level. This implies that OLS provides consistent estimates (although the power of the test may not be high). In addition, examination of the residuals shows that these are approximately normally distributed. The estimated parameters are very similar for both models, and in most cases are not statistically different from each other. In general, the reduced form estimated coefficients are in accordance with the literature on transport mode choice (Madan and Groenhout, 1987; Jara Diaz and Videla, 1989; Asensio, 2002).[23] The

[22]Note that maximum speed restrictions are, from an economic point of view, not an absolute constraint, since people can, and do, exceed maximum speed levels at the risk of paying a fine (Gander, 1985). The point is, however, that some individuals face different maximum speed restrictions.

[23]The reduced form estimates are broadly consistent with those of Fosgerau (2005a), who analyses the speed of car drivers who also travel for different purposes other than commuting, arguing a positive relationship between speed and income due to the presence of speed limit fines. In this study for Denmark, the income elasticity is smaller than we find (about 0.02 to 0.03) and the distance elasticity is about 0.20.

Table 2
Parameter Estimates and Statistical Tests. Dependent Variable = Log Speed

	OLS Estimation			*IV Estimation*			
	Coefficient	*s.e.*	*Prob.*	*Coefficient*	*s.e.*	*Prob.*	*Mean*
Constant	0.396	0.030	0.000	0.702	0.204	0.001	0.00
β_w							
Log Income	0.088	0.008	0.000	0.126	0.026	0.000	2.51
β_d							
Log Distance	0.492	0.004	0.000	0.403	0.059	0.000	4.31
β_z							
Woman	−0.047	0.011	0.000	−0.064	0.016	0.000	0.42
Age 18–34 years	0.002	0.010	0.826	0.014	0.013	0.275	0.39
Age >65 years	−0.071	0.040	0.078	−0.071	0.041	0.084	0.02
Part-time Employed	0.037	0.017	0.029	0.010	0.024	0.666	0.15
Self-employed	0.042	0.025	0.095	0.026	0.028	0.358	0.04
1 Adult in household	−0.054	0.017	0.001	−0.077	0.023	0.001	0.10
3+ Adults in household	−0.007	0.015	0.651	−0.010	0.016	0.527	0.12
Children in household	0.018	0.010	0.091	0.013	0.011	0.244	0.37
β_x							
Population density							
<1 persons/hectare	0.072	0.020	0.000	0.068	0.020	0.001	0.10
15–39.9 persons/hectare	−0.039	0.013	0.003	−0.054	0.016	0.001	0.35
40+ persons/hectare	−0.141	0.016	0.000	−0.162	0.021	0.000	0.24
Municipality size							
London	−0.328	0.018	0.000	−0.324	0.019	0.000	0.12
Other Metro Areas	−0.085	0.016	0.000	−0.091	0.017	0.000	0.14
Cities over 100 k	−0.051	0.014	0.000	−0.058	0.015	0.000	0.23
Villages under 3 k	0.068	0.020	0.001	0.092	0.026	0.000	0.09
Dummy 1999–2001	−0.006	0.011	0.596	0.006	0.013	0.675	0.34
Observations	9361			9361			
Adjusted R^2	0.671			0.655			
F[18,9345]	1060.7	Prob = 0.000		988.7	Prob = 0.000		
Akaike Criterion	1.320			1.365			
Hausman test F-statistic				2.398	Prob = 0.122		

income elasticity of speed is estimated as 0.09 (OLS) and 0.13 (IV) and the elasticity of speed with respect to distance as 0.49 (OLS) and 0.40 (IV). Statistically, there is little difference between the estimates.

The characteristics of residential location are shown to be highly significant with both estimation procedures. Commuting speed declines as population density increases, and also declines as the population of the municipality increases. Both of these reflect the higher congestion in built up areas and the availability and more prevalent use of public transport. Regarding the other variables, we find that commuting speed is lower for women and for the over-65s. The part-time employed and the self-employed appear to travel at higher speeds than the full-time employed according to the OLS estimates, but the IV estimates indicate that this effect is spurious. Individuals who are the sole adult in the household travel slower than those in households with two or more adults. Those with children appear to travel faster, but not significantly so. The results show further that commuting speed has *not* increased over the decade, *ceteris paribus*.[24]

4.0 The Structural Parameters and the Effect on the Commuting Costs

Given the reduced form estimates, we are able to calculate the structural parameters α_s, α_d, α_z and α_x (see Table 3). We will discuss the IV estimates in more detail, but note that the OLS estimates tend to give somewhat higher values, because the point estimate of β_w is somewhat smaller. We have seen that $\beta_w = 0.13$ (s.e. $= 0.03$), it appears therefore that the speed elasticity of monetary costs $\alpha_s = 6.9$ (s.e. $= 1.4$, see equation (14)), so $\alpha_s > 1$. The main consequence is that the monetary costs are a convex function of speed. As α_s is quite large, the marginal cost of commuting is extremely high at higher speed levels. We believe this makes sense. At certain higher levels of speed, commuters are essentially constrained due to speed limits and the increased risk of an accident. Further, fuel costs rise steeply with speed. The estimates also imply that at low speed levels, the marginal costs are close to zero, this also makes sense. For example, the additional monetary costs of switching from walking to the use of a bicycle (which increases the speed level by a factor four) are modest.

Recall that by choosing an optimal speed level, the ratio of variable monetary costs to time costs is equal to α_s^{-1}. It follows that the ratio of variable monetary costs to time costs is equal to 0.14 (s.e. $= 0.06$). Such a result is consistent with the mode choice literature where it is found that exogenous travel time changes in transport modes are seen as a more

[24] A number of other models were estimated, which confirm the robustness of the results. For example, we have estimated a number of models with OLS allowing income and distance to interact and to allow for a non-constant distance elasticity. The interaction appears to be small in value and statistically insignificant. Further, the distance elasticity declines slightly with distance. The only exception are specifications that do not include the logarithm of distance but merely distance. The latter specification is however mis-specified as, for example, evidenced by a much lower R^2.

Table 3
Structural Parameters and Effects of Variables on Commuting Costs

	(1) Commuting costs		(2) Monetary costs		(3) Value of time	
	Estimate	*s.e.*	*Coefficient*	*s.e.*	*Coefficient*	*s.e.*
			α_s			
Speed			6.944	1.401		
Log Income	0.874	0.026				
			α_d			
Log Distance	0.597	0.059	−3.141	0.691		
					α_z	
Woman	−0.444	0.222			−0.508	0.254
Age 18–34 years	0.097	0.090			0.111	0.103
Age >65 years	−0.492	0.284			−0.563	0.325
Part-time Employed	0.069	0.166			0.079	0.190
Self-employed	0.180	0.194			0.206	0.222
1 Adult in household	−0.534	0.319			−0.611	0.365
3+ Adults in household	−0.069	0.111			−0.079	0.127
Children in household	0.090	0.076			0.103	0.087
Population density			α_x			
<1 persons/hectare	−0.068	0.020	−0.540	0.159		
15–39.9 persons/hectare	0.016	0.429	0.127	0.054		
40+ persons/hectare	0.162	0.021	1.286	0.167		
Municipality size						
London	0.324	0.019	2.571	0.151		
Other Metro Areas	0.091	0.017	0.722	0.135		
Cities over 100 k	0.058	0.015	0.460	0.119		
Villages under 3 k	−0.092	0.026	−0.730	0.206		
Dummy 1999–2001	−0.006	0.013	−0.048	0.103		

Note: In column (1), the (marginal) effects on the logarithm of the (variable) commuting costs (given the optimal speed level) are reported, using Table 1, column 2. Columns (2) and (3) report the structural parameters which can be interpreted as the (marginal) effects on the logarithm of the (variable) monetary commuting costs and value of time respectively.

relevant factor than monetary costs (for example, Madan and Groenhout, 1987; Asensio, 2002). It is also consistent with the study by Littman (1999) that uses a different methodology in a different context, but which reports also that the time costs are much larger than the variable monetary costs.

Recall that the parameter α_d can be interpreted as the distance elasticity of the monetary costs per distance. The results imply that α_d is negative and is equal to -3.1 (s.e. $= 0.7$),[25] see equation (12). Hence at longer distances,

[25]The standard error is calculated using the delta method, see Goldberger (1991).

the results imply that the marginal monetary costs are substantially lower, which is consistent with the observation that commuters at longer distances travel much faster (as we have argued before, the fixed monetary costs will probably increase with distance, so $\alpha_d + 1$, the distance elasticity of the variable monetary costs may be negative). One may argue that it is more insightful to focus on the effect of distance on the (variable) commuting costs given the optimal speed level. Employing (18), it appears that the derived distance elasticity of the commuting costs is about 0.6 (see Table 3). It appears further (see (23)), that the derived distance elasticity of the marginal monetary commuting costs is 0.19 (s.e. = 0.12), which is statistically not different from zero at the 5 per cent significance level (of course, the marginal total commuting costs are zero by assumption). Consequently, the effect of speed on the monetary costs does not appear to depend on distance, when the speed is optimally chosen.

The parameter α_x measures the effect of background characteristics on (the logarithm of) the monetary commuting costs. For example, it follows (using (13)), that in London the implied (marginal) monetary costs are much higher. *Ceteris paribus* (so given the same arbitrarily chosen speed level), the (marginal) monetary costs are about 13 times higher ($\exp(2.57) = 13$) than in small cities. One may again argue however that it is less insightful to focus on the effect of X given arbitrarily chosen speed levels, because the optimally chosen speed level is different in London than elsewhere. In London (compared to municipalities with a size between 3 and 100k inhabitants and given the lower optimally chosen speed level) the marginal monetary costs are 'only' about 2 times higher (see equation (22), $\beta_x = 0.324$ and $\exp(0.648) = 1.91$), whereas the monetary costs are 'only' 1.38 times higher ($\exp(0.324) = 1.38$, see (17)). Hence, we interpret the results as follows. Given the same speed level, the (marginal) monetary costs are much higher in London than elsewhere. Subsequently, the commuters choose lower speed levels in London than elsewhere to decrease the marginal monetary costs. Still, in the optimum, the marginal monetary costs are higher in London, since the marginal benefits are decreasing in speed, so the marginal benefits are higher in London. One of the consequences is that the implied variable monetary costs are about 30 to 40 per cent higher in London given the chosen speed level.

The parameter α_z measures the effect of Z on (the logarithm of) the value of time $\psi(Z)$. It follows that the value of time of women is about 40 per cent less ($\exp(-0.508) - 1 = -0.40$) than for men, *ceteris paribus*, but other individual characteristics have no statistically significant effect. Note that because the speed elasticity of the monetary costs α_s is large (that is, the monetary costs are a convex function of speed), a relatively small value for β_z has a large effect on α_z (for women, β_z is -0.064, see Table 2). This implies that relatively large differences in the value of time between individuals have little effect on the chosen speed level.[26]

5.0 Conclusion

In this paper, we have estimated a structural model of optimal speed choice, which can be derived from a reduced form regression of speed on income and distance. The model has been applied to the UK for the years 1989–1991 and 1999–2001. Our estimates imply that the elasticity of speed with respect to income is approximately 0.13, and that the total travel costs mainly consist of time costs. For the average commuter, the variable monetary costs are estimated to be about 14 per cent of the total variable costs. An implication of this is that as incomes rise commuters choose faster modes, despite their higher monetary costs. This has been an important factor in the growth of commuting by car in the past decades. For example, during the 90s the percentage of work trips made by car in Britain increased from 65 per cent to 70 per cent. However, with increasing congestion, the time-costs of car travel will increase, but unless faster public transport modes are available or their monetary costs decline substantially in relation to car travel, there will be little incentive to switch to public transport. We believe that our results are especially of interest for developing countries such as China and India where the anticipated increase in income and the growth in car ownership is substantially higher than in developed countries. The results suggest that to address the issue of increasing congestion, it is particularly relevant to develop a fast and efficient public transport system.

We find that the monetary costs of speed are a convex function of speed: at high levels of speed, monetary costs increase strongly (for example, due to the increased risk of accidents, fines and so on), so the marginal costs

[26] As stated above, the identification of the structural parameters relies on the assumption of a unity elasticity for the value of travel time with respect to income. Let us suppose now that the elasticity is much less than one, about 0.6 as reported by Small *et al.* (1999). In this case it can be seen that the value of all structural parameters are about 40 per cent less, except α_s which would be 3.8 so about 50 per cent less. Although the structural parameters are therefore strongly affected, the main conclusions remain essentially identical: α_s would still be much larger than one, so the monetary cost function is convex; the ratio of variable monetary costs to travel time costs is 0.26, so the time travel costs are much larger than the monetary costs. Note that the reduced form estimates are not affected and that all marginal effects reported in Table 1 are not affected (except those with respect to income).

become essentially infinite. Our results imply that differences in the value of time between individuals have little effect on the chosen speed level. Finally, it appears that the (marginal) monetary costs of speed are a positive function of the population density and municipality size, *ceteris paribus*. For example, in London, the variable monetary costs of speed are about 13 times as large as in small cities, *ceteris paribus*. Nevertheless, given the optimally chosen speed level, which is much lower in London due to speed restrictions and congestion which increases the risk of accidents (Verhoef and Rouwendal, 2001), the variable marginal costs are 'only' 30 to 40 per cent larger.

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