

The impacts of household structure to the day-to-day variability of individual and household stochastic travel time budget

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Keywords: travel time budget, household structure, stochastic frontier model, UK national travel survey

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The impacts of household structure on the individual stochastic travel and out of-home activity time budgets

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The amount of time individuals and households spend in travelling and in out-of-door-activities can be seen as a result of complex daily interactions between household members, influenced by opportunities and constraints which vary from day to day. Extending the deterministic concept of travel time budget to a stochastic term, and applying a Stochastic Frontier Model to a dataset from the 2004 UK National Travel Survey, this study examines the hidden stochastic limit and the variations of the individual and household travel time and out-of-home activity duration– concepts associated with travel time budget. The results show that most individuals may not have reached the limit of their ability to travel and may still be able to spend further time in travel activities. The analysis of the model outcomes and distribution tests show that among a range of employment statuses, only full-time workers' out-of-home time expenditure has reached its limit. Also observed is the effect of having children in the household: children reduce the flexibility of hidden constraints of adult household members' out-of-home time, thus reducing their ability to be further engaged with out-of-home activities. Even when out-of-home trips are taken into account in the analysis, the model shows that the dependent children's in-home responsibility reduces the ability of an individual to travel to and to be engaged with out-of-home activities. This study also suggests that, compared with the individual travel time spent, the individual out-of-home

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INTRODUCTION

The amount of time people spend on routine activities has been explored by social scientists in a range of contexts. The striking empirical evidence about the amount of time people spend in travelling is that it is approximately the same (on average) for people of different characteristics, and that in many countries and societies it has remained constant, or at least stable, over many years. Ever since the work of Zahavi and his colleagues in the late 70s, it is common to interpret the observed constancy of travel time as signifying the existence of “travel time budget” (TTB) - a fixed and stable amount of time that an individual can make available for travel. A number of studies have observed the constancy and stability of travel time at the aggregated level (e.g. Goodwin, 1973; Tanner, 1979; Zahavi and Talvitie, 1980; Zahavi and Ryan, 1980; Newman and Kenworthy, 1999; Schafer and Victor, 2000). Most of these studies reported on robust evidence to support the idea of a stable amount of daily travel time, suggesting that on average, individual would spend about 1 to 1.5 hours per day for travelling.

Gunn (1981) reviewed TTB approaches and argued that many of them have been based on the assumption that the characteristics of an individual’s travel behaviour are affected by the total amount of travel he or she performs, implying that TTBs are in some sense have been determined prior to the actual travel (and therefore can be used to have it predicted). It might be argued that the idea of constant travel budgets is in conflict with rational economic behaviour (Tanner, 1979). Goodwin (1973) constructed simplified models of travel time use to demonstrate that stable travel times could arise even when travel behaviour is not explicitly constrained to reproduce them.

Interestingly, despite the large amount of work done in this area for more than 40 years and the wide range of empirical evidence that firmly support the TTB concept, the reason underlying this phenomenon is still unknown (Mokhtarian and Chen, 2004). Some studies at the disaggregate level (Kirby, 1981; Kitamura *et al.*, 2006) show that travel routines and TTBs are not constant but rather are a function of several variables. Therefore, it might be hypothesized that there may be an unseen or hidden (to the modeller) limited amount of time budget, which has been spent and constrained on various ‘common’ daily travel-activity trade-off engagements and which has left a small variance in the observed individual total travel time which may seem stable at the aggregate level.

Given that in the last three decades there have been enormous changes in the physical and social environments of trip making it might be argued that the variance in the observed amount of time allocated for individual travel is becoming more complex and less predictable and so are the number of trip chains and total travel time the individual may spend and engage in. Various new commodities, appliances and services have been introduced to reduce the time required for domestic chores such as cleaning, cooking and gardening. In many countries, two-worker households have become a social norm rather than an exception, changing the way in which household tasks are carried out by its members. All of these changes affect the needs for, resources available for, and constraints imposed on travel (Susilo and Kitamura, 2008). For example, many dual-

earner households share their household obligation trips, such as drop-off and pick-up children, with other household members. This possible interaction, or even substitution, of travel time between members of the same household (which is hidden at the individual level), have led some researchers (e.g. Habib and Miller, 2009; Chikaraishi *et al.*, 2010; Arentze *et. al.*, 2011) to promote the use of household rather than individual TTBs. Moreover, recent studies on socio-psychological aspects of travel behaviour, such as social interactions between household members (Bhat and Pendyala, 2005) and pro-social orientation of household members (Arentze and Timmermans, 2006) demonstrate that shared intra-household activities have a strong effect on individual travel patterns. According to social exchange theory, social behaviour can be seen as an exchange of goods (material or non-material) in a process of influence that tends to work out at equilibrium to a balance in the exchanges (Homans, 1958). Thus, patterns of time allocation between household members might be the outcome of a process in which they try to maximize utilities based on the available resources of the household. This argument is supported by recent works that have explored the activity time allocation of the male household head and the female household head (Zhang *et al.*, 2005; Cao and Chai, 2007; Chikaraishi *et al.*, 2012). However, the role of the household structure and the intra-household interactions between household members in generating (or reducing) the travel time of individuals and households is largely unknown. It is therefore important to explore how the effect of household structure (i.e., number of children) on the hidden boundary of individual travel time expenditure.

It is important to understand and predict how far individuals could be expected to adapt and change their behaviour given changes to their household structure and their hidden time allocation constraints. Applying a Stochastic Frontier Model to a dataset from the 2004 UK National Travel Survey, this study explores the nature of the hidden TTB's boundaries at the individual level, and how they might vary for different types of household structures. In the next section, the possible existence of the hidden (stochastic) TTB and the theoretical aspects of the stochastic frontier model are discussed and formulated. This section is followed by a description of the dataset. Analysis of the day-to-day variability of the TTB hidden boundaries is presented. Also analysed is the impact of the household size and household structure on time budget boundaries. The paper is concluded with a discussion on the salient findings and their implications.

STOCHASTIC FRONTIER MODEL AND THE HIDDEN CONSTRAINTS

The idea of *hidden (stochastic) time budget* introduced in this work has originated from the understanding that the amount of time allocated for travel (and other activities) by individuals and households can be seen as a result of complex daily interactions between household members, influenced by a range of other factors which vary from day to day. As suggested by both social exchange theory and activity-based models, such time allocations are largely shaped by opportunities and constraints individuals are faced with. Studying individuals' spatial movement, Hägerstrand (1970) classified the individual constraints into three categories: capability constraints, coupling constraints, and authority constraints. The *capability constraint* means that an individual's activities are

limited by his/her ability to be engaged in activities. It is not only a geographical boundary, but also has time-space walls on all sides that limit the possibility of the individual to be engaged in activities. The *coupling constraint* means that the freedom of individual's activities is bounded by where, when, and for how long the individual has to join with other individuals. The *authority constraint* relates to the time-space aspects of an authority – a time-space entity within which events are under the control of a given individual or a given group (e.g. government's rules on shop opening hours). These constraints define time-space prisms in which the individual's trajectory in time and space must be contained. Under the assumption that each individual has his/her own home base, and needs a certain number of hours a day for sleep and for maintenance activities at the home base, there exist boundary walls in time and space beyond which he or she cannot encroach. The walls shape a prism in time and space, and also shape the daily amount of time an individual can spend on travel and out-of-home activities.

At the same time, it can be argued that an individual also has the desire to travel and explore (Huff and Hanson, 1990; Susilo and Dijst, 2009), spread their choice risk due to their knowledge limitation (e.g. Mercado *et al.*, 2012), include better opportunities in their destinations and activities choice sets, and reduce uncertainty by learning all viable options (e.g. Morency *et al.*, 2012). Furthermore, some recent studies (e.g. Mokhtarian and Solomon, 2001) show that travel may not necessarily be a derived demand but can constitute an activity in itself which has positive utility components. Therefore, whilst the individual may be constrained by the walls of prisms that represent the *maximal* amount of travel time that he or she would like to spend, there may also be another set of walls of prisms that represents the amount of *minimal* travel time that the same individual would need to spend as this time is competing with other activities that carry larger benefits to him/her. These 'pull' and 'push' factors, that work in opposite directions, would affect the amount of time that we spend on travel and activities we are engaged in, as shown at Figure 1. The time allocated for the individual's travel activities would therefore be inside the prism, in between those two boundaries. As lifestyles, constraints and personal preferences vary among individuals it is likely that heterogeneity will be exhibited in TTB's boundary conditions.

[Figure 1 is about here]

The concept of the prism is extremely useful, both as a conceptual framework and as a construct for the formulation, analysis and prediction of travel behaviour. It is difficult however to observe the prism itself in a direct way; what mostly can be observed are the time-space paths that represent the individual's movement inside a prism, from which only a sub-region of it can be identified. Furthermore, there are always unobserved conditions and events that may cause the individual not to spend as much of their travel time as they desire.

In order to explore the hidden TTB's boundary conditions, stochastic frontier modelling is used in this study. Stochastic frontier model is an econometric modelling technique that is used to explore the maximum or minimum limit of outputs that are unachieved, therefore unobserved, due to various internal and external conditions. The stochastic

frontier model was first proposed by Aigner *et al.* (1977) in the context of production function estimation to account for the effect of technical inefficiency. The inefficiency causes actual output to fall below the potential level (that is, the *production frontier*) and also raises production cost above the minimum level (that is, the *cost frontier*).

The canonical formulation that serves as the foundation for other recent variations of stochastic frontier models is formulated in Aigner *et al.* (1977)'s model:

$$Y = \beta'X + v - u, \quad (1)$$

where y is the observed outcome (goal attainment), $\beta'x + v$ is the optimal frontier goal (e.g., maximal production output or minimum cost) pursued by the individual, $\beta'x$ is the deterministic part of the frontier and $v \sim N[0, \sigma_v^2]$ is the stochastic part of it. The two parts together constitute the 'stochastic frontier'. The amount by which the observed individual fails to reach the optimum (the frontier) is u , where $u = |U|$ and $U \sim N[0, \sigma_u^2]$ (the term $v - u$ would be changed to $v + u$ for a stochastic cost frontier or any setting in which the optimum is a minimum). In this context, u represents the '*inefficiency*'.

Applying eq. 1 to the individual travel time budget context, the general form of stochastic frontier models used is:

$$Y_{it} = \beta'X_{it} + \varepsilon_{it}$$

where

$$\varepsilon_{it} = v_{it} + u_{it} ; \text{ for production frontier} \quad (2a)$$

$$\varepsilon_{it} = v_{it} - u_{it} ; \text{ for cost frontier} \quad (2b)$$

with i is the observation case; t is the observation time; Y_{it} are observed dependent variables; β 's is a vector of coefficients; and X_{it} are explanatory variables.

v_{it} are random error terms vary across individual and time (assumed to have a normal distribution, $-\infty < v_{it} < +\infty$), and

u_{it} are random error terms that represent the inefficiencies of the output/choice which are below the frontier limitation.

Two possible distributions are proposed for u_{it} by Aigner *et al.* (1977): a half normal distribution and a negative exponential distribution. Following the findings reported in previous studies (e.g. Yamamoto *et al.*, 2004) that have implemented a stochastic frontier model with departure time estimation, it is assumed in this study that the u_{it} error term is to have a half normal distribution, $u_{it} > 0$.

It is assumed that equations 2a and 2b are subject to:

$$\begin{aligned} E[v_{it}] &= 0, E[u_{it}] \geq 0; E[\alpha_i v_{it}] = E[\alpha_i u_{it}] = E[v_{it} u_{it}] = 0 \\ E[\alpha_i \alpha_j] &= E[v_{it} v_{jq}] = E[v_{it} v_{jt}] = E[u_{it} u_{jq}] = E[u_{it} u_{jt}] = 0 \end{aligned} \quad (3)$$

where: $i \neq j, t \neq q, i, j = 1, 2, 3, \dots, N$ behavioural unit (individual); $t, q = 1, 2, 3, \dots, T$ observed time. This model assumes the following distribution of the error term (Aigner *et al.*, 1977):

$$h(\varepsilon_{it}) = \frac{2}{\sigma_t} \phi\left(\frac{\varepsilon_{it}}{\sigma_t}\right) \left\{ 1 - \Phi\left(\frac{\varepsilon_{it} \lambda_t}{\sigma_t}\right) \right\}, -\infty < \varepsilon_{it} < \infty \quad (4)$$

where $\sigma_t^2 = \sigma_{u_t}^2 + \sigma_{v_t}^2$, $\lambda_t = \sigma_{u_t} / \sigma_{v_t}$, ϕ and Φ are the standard normal density and cumulative distribution functions, respectively, $v_{it} \sim N(0, \sigma_{v_t}^2)$, and u_{it} is the density function,

$$g(u_{it}) = \frac{2}{\sqrt{2\pi}\sigma_{u_t}} \exp\left[-\frac{u_{it}^2}{2\sigma_{u_t}^2}\right], \quad u_{it} \geq 0, t = o, t. \quad (5)$$

The expected value and the variance of u_i are evaluated for the half normal models as

$$E[u_i] = \sqrt{\frac{2}{\pi}} \hat{\sigma}_u, \quad Var[u_i] = \left(1 - \frac{2}{\pi}\right) \hat{\sigma}_u^2, \quad (6)$$

Stochastic Frontier in predicting the limit of travel time spent

In travel behaviour research stochastic frontier models have been recently proposed as a means to estimate the location of an unobserved prism vertex of individual trip departure and arrival time (Kitamura *et al.*, 2000; Pendyala *et al.*, 2002; Kitamura *et al.*, 2006). Further, Soo and colleagues (Soo, *et al.*, 2008; Soo, 2009) used this model in exploring multi-peaks distributions of arrival and departure time and how these differ between genders. In this particular study, the observed individual's total daily travel time and the amount of out-of-home time are used as the dependent variables of the stochastic frontier models, which in turn may be used to derive the prism vertex as the location of an unobservable frontier (in this case, the hidden lower and upper limits of the spent time, depending on the cases). The daily travel time and out-of-home time are both used as dependent variables in order to test whether the budget lies only at the individual travel time level or at the total out-of-home activities level. Given that an individual willingness to travel is highly influenced by the amount of the activity duration and that an individual have to trade-off between their travel distance and activity duration in selecting their activity locations (Susilo and Dijst, 2010), it is reasonable to expect that the prism's boundary may not lie solely on travel budget but in total out-of-home that individual have to spend.

The general form of stochastic frontier models adopted in this study is: $Y_{it} = \beta' X_{it} + \varepsilon_{it}$, where: $\varepsilon_{it} = v_{it} + u_{it}$ for the case where the individual has reached their time budget, and $\varepsilon_{it} = v_{it} - u_{it}$ for the case where the individual has not reached their time budget; with i = observation case; t = observation time; Y_{it} = observed dependent variables (individual travel time and out-of-home time); β' = vector of coefficients; and X_{it} are explanatory variables, based on observed characteristics (heterogeneity) across individual, variant across time and individual, including their household structure.

As it is not known whether individuals have already reached their time budget limit or not, both the cost and production frontier approaches are tested in the cases studied in this work (as illustrated in Figure 2). It can be hypothesized that some people, such as the young and unemployed, may have less tight time constraints and less travel needs than

full-time workers. Therefore their entire travel budget might not have been fully allocated and their time use distribution might be close to the minimum amount of travel that they need to do (not as a derived demand, but as a positive utility). On the other hand, some full time workers might also have rather demanding out-of-home commitments which will exhaust their entire out-of-home time expenditure budget and any extra time demand, such as having dependent children, may force them to make trade-offs. Such hypotheses are explored in the next sections.

[Figure 2 is about here]

In the analysis presented in this work the individual socio-demographic factors, and their household structure, are used as explanatory variables in exploring the stochastic frontier of their travel time use. A caveat is due here; the time constraints discussed are mainly focused on the out-of-home activities. Due to data limitations we do not have information regarding in-home constraints (e.g. house cleaning and baby sitting at home that may act as time constraints for housewives). In this study, unless an individual has a production frontier distribution, it is assumed that the individual has not yet reached their time expenditure limit.

The other plausible hypotheses of the analysis are:

1. The hidden boundary (budget limit) of individual travel time and out-of-home time may exist. However, the limits might not be observable unless the individuals have been significantly ‘pushed’ to the boundary by their out-of-home commitments.
2. The effect of household structure (number of children and number of adult members) on the trade-off between individual time expenditure and their limits may vary depending on individuals’ out-of-home commitments.

THE USED DATASET AND THE DISTRIBUTION OF THE TRAVEL TIME AND OUT-OF-HOME TIME

This paper draws on data from the 2004 UK National Travel Survey (NTS) which provides detailed information about individuals, households and their 7-days trip engagements (see National Statistics and DfT, 2005). The UK NTS is a series of household surveys designed to provide regular, up-to-date data on personal travel and monitor changes in travel behaviour over time. In total, 12,209 travellers from 6,233 households are included in this analysis. The *unweighted* samples’ travel characteristics in the datasets are summarized in Table 1. The *children* variable in this analysis is defined as the number of household members who are less than 15 years old. In the analysis, the trips are classified into three different groups based on the main benefactor of the journey. *Personal trips* include commuting and various personal business trips. *Mixed trips* include food and non-food shopping, visiting a friend, entertainment, sport and holiday trips. *Escorting trips* include pick-up and drop-off trips, shopping and all trips that were reported by the respondent as an escorting activity. *Out-of-home activities*

mean all activities that are carried out away from the home, including work and school trips. The 2004 NTS is chosen for this analysis because it is the most recent UK dataset that provides the detailed level of household structure coding that is required in our analysis. The more recent UK datasets use more general categorisation in recording household structure.

The number of trips in this study is calculated based on the number of activities that are involved on these particular trips. Each trip represents one activity. A trip chain may contain two or more activities or trips. However, transfers between travel modes at the same trip (from public transport to walking for instance) are not treated differently in this analysis.

To avoid a violation of the IIA assumption over the observation, we only use the average travel pattern over available observations, which were assumed to provide a good representation of the ‘*typical day pattern*’ of the individuals. As for the household level, since most of the selected samples represent households with one adult who is working as a full-time worker whilst the other one is either a part-time worker or unemployed, the model was estimated for full-time workers, unemployed and part-time workers separately; therefore, it was assumed that any IIA violations at household level can be ignored.

The amounts of the individual’s travel time and out-of-home time spent by different types of household structure is shown at Tables 2 and 3, respectively. Table 2 shows the total amount of the individual’s travel time on the given day (Table 2a) and the total amount of his/her out-of-home time expenditure on the given day (Table 2b). Table 3 shows the similar amount on household level: Table 3a shows the total amount of travel time for the whole households on the given day and Table 3b shows the total out-of-home time expenditure for the whole household. The later parts of Tables 2 and 3 show how the amount of spent travel time and out-of-home duration increases with the increase in the number of household members, compared to households without children and to a-single-person households, respectively. Another caveat is due here. As the number of households in the sample that have three or more children (5% of the whole household size), or three or more adults (13% of the whole household size), are relatively small, we need to treat values associated with such adult/children combinations carefully.

[Table 1 is about here]

Table 2a shows that the average amounts of individual travel time at households of different structures are very similar (between 67-80 minutes), despite the range of household types that were examined. The daily-travel-time-spent changes due to the changes in the number of children or adults within the household are small and the incremental patterns do not show any clear changes patterns – except for one case: for each child at a single-parent household, the average parent’s daily spent travel time is reduced by about 2 minutes per child (up to two children), whilst having a spouse would enable the parent to share the household chores; in such a case, the individual parent’s average daily travel time reduction is about 0.75 minutes per day.

Table 2b shows that the higher the number of adults within a household is, the more time an individual would spend on their daily out-of-home time expenditure. Presumably, they spent this additional time to be engaged in various shared activities (because the average spent travel time is not significantly different, see Table 2a). In a household with children, having an additional adult increases the average out-of-home time expenditure of household members by about 23 minutes per day. There is no clear pattern of such increase of time as a result of an increase in the number of children within household (see Table 2b).

[Table 2 is about here]

[Table 3 is about here]

Additional insights on the patterns of changes to time expenditure can be gained from having the household as the unit of analysis (see Table 3). The effect of having a single child at the household (in comparison to a non-children household) is an increase of the household's travel time expenditure by a daily average of 52 minutes, whilst having a second and third child at the household increases the average household's travel time expenditure by 50 and 44 minutes, respectively. On the other hand, it can be observed that, in a household with up to one child, an increase in the number of the adults by one and two increases the daily average household's travel time expenditure by 50 and 41 minutes, respectively.

It is more difficult to observe specific time-use patterns from the analysis of households' out-of-home time expenditure level (Table 3b). However, it can be seen that an incremental increase on the household's out-of-home time expenditure resulting from having an additional child(ren) at the household is higher than an increase resulting from having an additional adult(s) within the household.

All of these tendencies that are shown in Tables 2 and 3 are also results of the interactions of household members' intra- and out-of-home activity-travel engagements with each individual's hidden travel time budget. These interactions are further revealed in the next section, in which the Stochastic Frontier Model is applied to analyse the distributions of the observed variables and to explore how they are linked to individual's socio-demographic characteristics.

HOW SIGNIFICANT IS THE HOUSEHOLD STRUCTURE IN PULLING AND PUSHING US TO THE LIMIT?

To understand how the interactions of household members' intra- and out-of-home activity-travel engagements, given their household structure, influence the individual's hidden travel time budget, the Stochastic Frontier Model is used in this section. The full-time and part-time workers' and unemployed daily travel time and out-of-home time

expenditures were estimated separately. All models and distribution tests reported in this paper were done with LIMDEP Version 9.0 by Econometric Software, Inc.

Testing the distributions of the observed behaviours

Prior model estimations, the distribution of individuals' travel time and their out-of-home time expenditure, by various combinations of household structures, were tested to determine whether cost or production functions should be used in explaining the phenomenon. In most cases the distribution of individuals' travel time expenditure are skewed to the left, which indicates that most individuals may not have reached their upper time limit for travel (similar to the cost-production case illustrated in Figure 2) and may still be able to spend further time in travel activity.

Further tests with Stochastic Frontier distributions against the observed travel time distribution shows that the observed travel time distribution does not have a production frontier (upper limit) but does have a cost frontier (lower limit) (see Figures 3a, 3c and 3e).

[Figure 3 is about here]

Also explored is the distribution of individuals' out-of-home time expenditure by various types of household structures. The distribution of out-of-home time expenditure shows an interesting pattern: it has two peaks – this suggests that the sample may be comprised from (at least) two different populations. Presumably this pattern is caused by the different levels of out-of-home commitments among individuals, which provide different flexibility in time allocation arrangement among different groups of individuals (this is supported by results reported by Susilo and Kitamura (2005) and Susilo and Axhausen (2007)). Further tests with Stochastic Frontier distributions against the observed travel time distribution show that the distribution of the full time workers' out-of-home time expenditure has a production frontier (upper limit) (Figure 3b) whilst that is not the case with unemployed and part-time workers (Figures 3d and 3f, respectively). Interestingly, Figure 3d shows the emergence of not only one cost frontier, but two. Further model estimations (not shown here) suggest that this is due to the time-space constraint differences between adult household members with and without children.

Salient results of the model estimations

The models were estimated with and without including the amount of trips engaged on the given day. The model estimation results can be seen at Tables 4, 5 and 6. Whilst it can be argued that the number of trips is a function of individual socio-demographic and household structure, given that not much information on in-home constraints is available, we believe it would be important to test whether, after the out-of-home engagements are taken into account, the household structure would matter in defining individuals' unseen time constraints. In these models, '*people who are older than 65 years old*', '*female*', '*low income parents*' and '*zero children in household*' are treated as the reference variables. '*Low income parent*' is defined for any parent who have earned less than 9,999

GBP per year, and '*high income parent*' for ones who have earned above 20,000 GBP per year. This categorisation of income groups is based on the classification that has been provided from the dataset itself. According to UK HMRC (2011), the median annual income before tax in the UK at 2004 was 16,000 GBP.

Table 4 shows that parents with high income have later travel time prisms vertex location than others, which shows that they have a higher minimum travel time need than lower income household (at an average difference of 4.28 minutes/person/day). Male full-time workers have earlier travel time prisms vertex location than female, which shows that males have less minimum travel time than females (about 1.36 minutes less), though this gender difference is only significant at $\alpha=10\%$. The household structure (number of adults and children) was not found to have a significant influence on the individuals' travel time prisms vertex location. This means that the household structure does not have significant effect on the minimum need of individual travel time for full time workers.

[Table 4 is about here]

However, unlike travel time models, the individuals' out-of-home time prisms vertex location shows much stronger relationship with their socio-demographic and household structure conditions. Males, younger people and high income parents have later prisms vertex location than females, older people and lower income parents. This shows that males, younger people and people with high income have more time to spend on out-of-home activities than their counterparts, which is in-line with previous studies, such as Chikaraishi *et al.* (2012). On the other hand, having children reduces the individuals' ability to be engaged in out-of-home activities significantly. Having one, two or three children in the household reduces the individuals' out-of-home prisms vertex location by about 27, 34 and 24 minutes, respectively. Even after taking into account the out-of-home individual trips having one or two children at the household has significantly reduced the individuals' out-of-home prisms vertex location by about 15 and 23 minutes, respectively. This shows that individual out-of-home time expenditure is not only constrained by out-of-home activities and trips that are associated with children's travel needs, but also by in-home child-bearing activities (about 15 and 23 minutes less than others, for one and two children household, respectively).

Unlike the full-time workers' cases, the minimum travel time of unemployed travellers is neither influenced by the gender, age, income nor number of children (see Table 5). However, the existence of another adult within the household marginally reduces the minimum of unemployed travellers (at $\alpha=10\%$). As for the out-of-home-time expenditures, those who are 24 years old or less and who are unemployed travel more than their counterparts. The unemployed who have access to private car also tend to travel marginally (at $\alpha=10\%$) more than their counterparts. Whilst at the same time, unemployed males have significantly lower minimum need of out-of-home-time than unemployed females.

[Table 5 is about here]

As for the case of part-time workers, the older groups have a higher minimum need of travel time than younger groups, especially if they are high income groups and have three children in the house; they would be likely to have a later travel time prisms vertex location than others (see Table 6). On the other hand, in terms of out-of-home-time expenditure, younger part-timer workers have a later travel time prisms vertex location than their counterparts – presumably, this is due to the different part-time jobs that those in these groups are involved in. It is likely that the younger part-time worker would be involved in more labour intensive occupations and may work for longer hours than their older counterparts. The higher paid part-time workers also marginally (at $\alpha=10\%$) tend to have a higher minimum need of out-of-home time expenditure than their counterparts. However, at the same time, having one, two or three children in the household reduces the minimum need of adults' daily out-of-home time expenditure by 27, 30 and 55 minutes, respectively. Even after the out-of-home trips have been taken into account, having two or three children still reduces the size of adults' hidden time-space prisms by 20 and 44 minutes, respectively.

[Table 6 is about here]

CONCLUSION AND DISCUSSION

Applying the Stochastic Frontier Model to a dataset from the 2004 UK NTS, this study aimed to explore the nature of the hidden travel time budget's boundaries of each individual and how it varies for different types of household structure. Further analysis with the Stochastic Frontier model shows that most individuals may have not reached their limit to travel and may still be able to spend further time in travel activity. The model and distribution tests show that it is only full-time workers' out of home time expenditure which has reached its limit. Having dependent children reduces the flexibility of adults' hidden out-of-home time constraints thus reducing their ability to be further engaged in out-of-home activities. Even after taking into account the personal and children related out-of-home trips, the model shows that the dependent children's in-home responsibility will still reduce the hidden boundary of individual ability to travel and engage in out-of-home activities. The analysis also reveals that some groups within the population (e.g. high income parents, younger people etc.) need more time to satisfy their daily minimum travel needs and also in doing their out-of-home travel and activities, whilst others (e.g. male full-time workers) need less.

Whilst a travel budget might exist, the study shows that most individuals have not fully allocated this time budget to their travel activities – only full time workers have reached their out-of-home time expenditure limit. It was also found that their household structure does not have a significant effect on the minimum amount of travel time they need, except for part-time workers who have two or three children within their households. This study also suggests that the individual out-of-home time expenditure may be considered as a better budget indicator in drawing the constraints in individual space-time prisms than the individual TTB.

The implications of this work are in contributing to better understanding (and possibly prediction) of how much individuals are likely to adapt to changes in their household structure and change their travel behaviour and time allocation patterns in response to such changes. We believe that the findings reported in the paper, and the methodology suggested in it, would be of relevance to modellers, travel planners and policy makers – although we are careful in not suggesting specific policy recommendations as the findings might require further validation and the effect of other variables, not included in the model, should be further explored. These would include joint activity-travel arrangements at household level, the day-to-day variability of the inter- and intra-household interactions to the individual travel time and out-of-home time expenditure.

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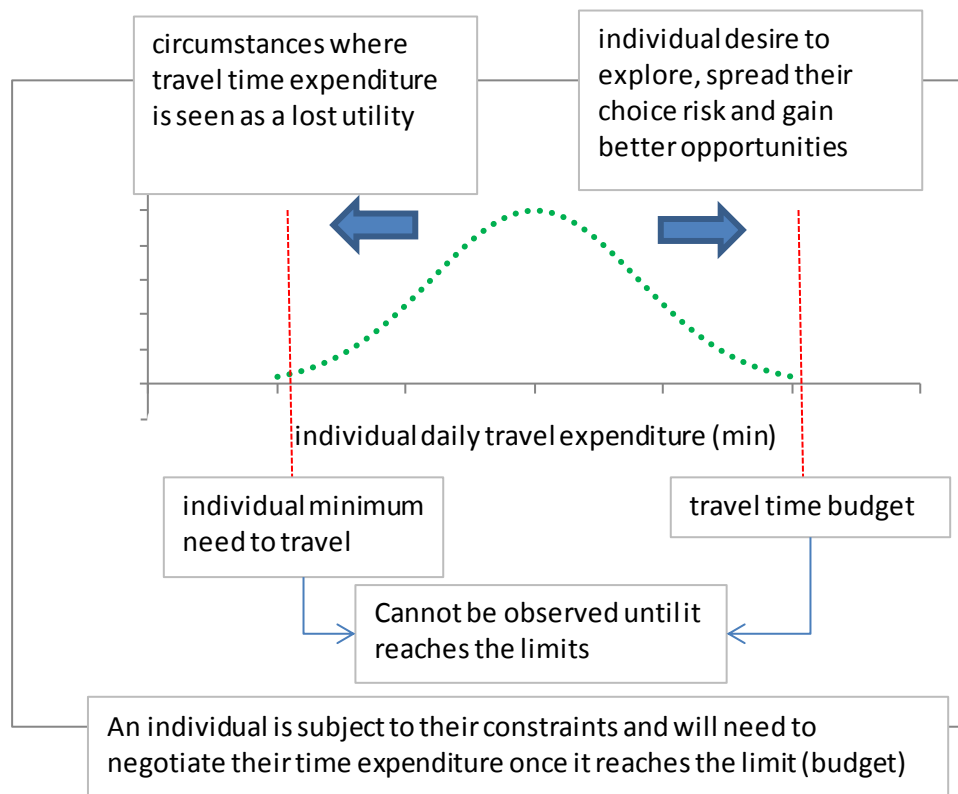


Figure 1. "Push and pull" in individual's daily time expenditure

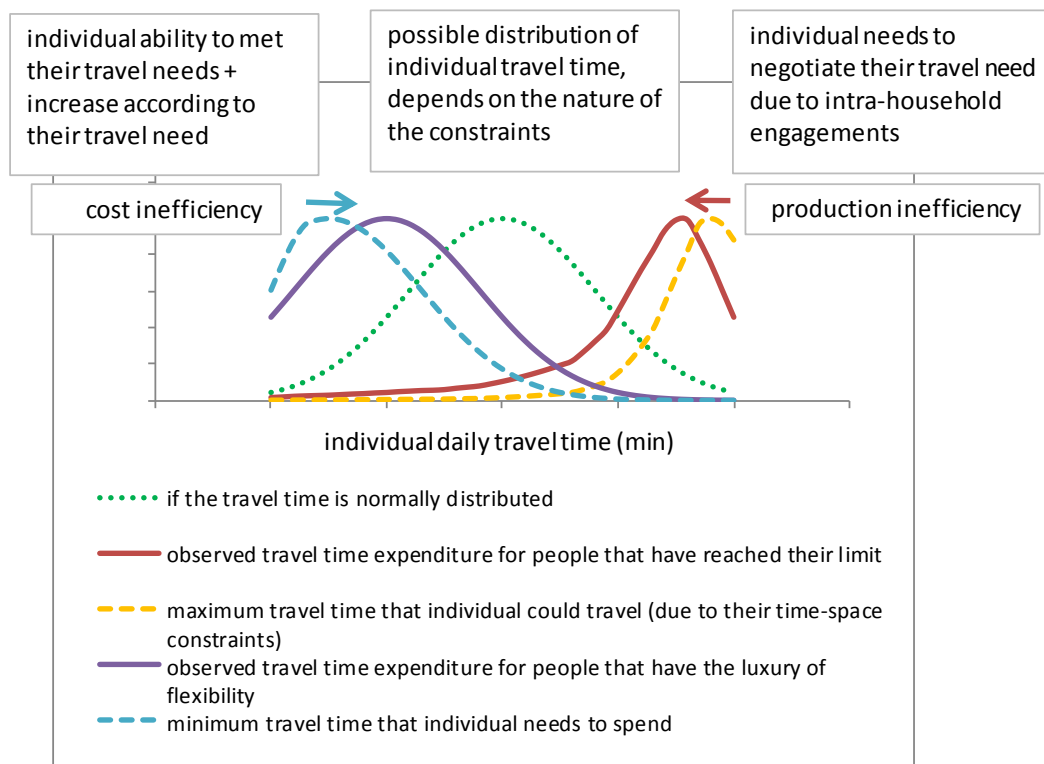
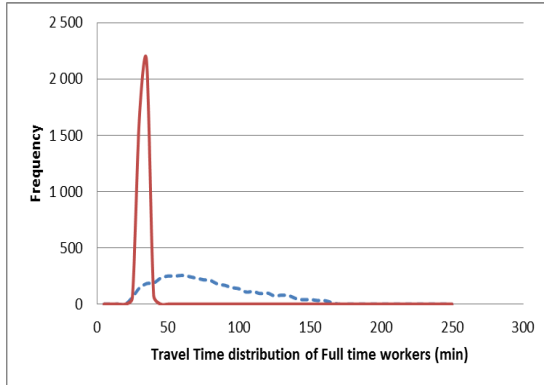
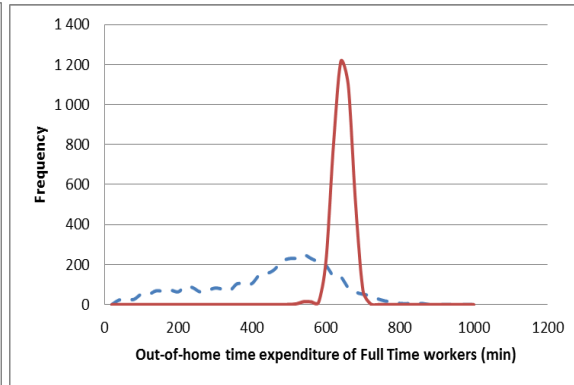


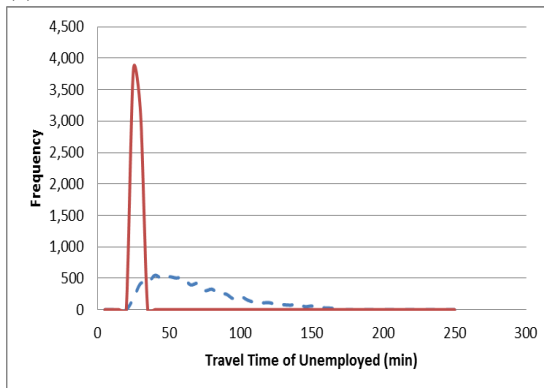
Figure 2. The observed travel time and the unseen boundary of individual time expenditure



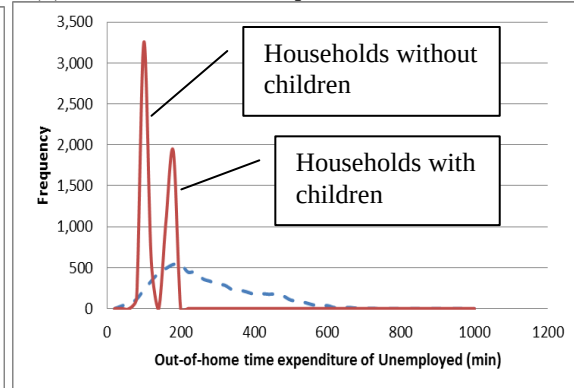
(a) Travel time distribution of FT workers



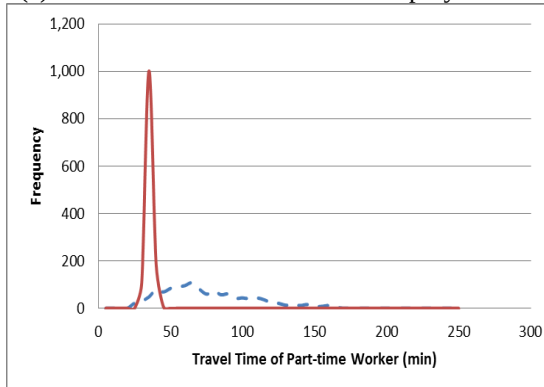
(b) Out-of-home time expenditure of FT workers



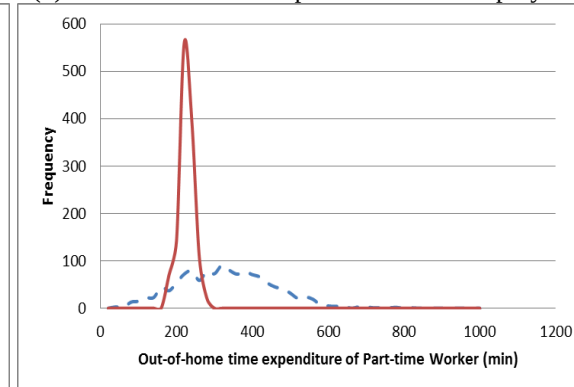
(c) Travel time distribution of Unemployed



(d) Out-of-home time expenditure of Unemployed



(e) Travel time distribution of Part-time Workers



(f) Out-of-home time expenditure of Part-time Workers



Figure 3. The individual's out-of-home and travel time expenditures: observed levels and Stochastic Frontier analysis

TABLE 1. The profiles of respondents' socio-demographic characteristics and travel engagements

<i>(a) Characteristics of Individual Socio-demographics</i>	
Male respondents	46.8%
Respondents 24 years old or less	27.6%
Respondents between 25 and 44 years old	29.2%
Respondents between 45 and 64 years old	23.3%
Respondents 65 years old or older	19.9%
Respondents who are full-time workers	32.4%
Respondents who are part-time workers	10.7%
Respondents who are unemployed	56.9%
No income parents	23.5%
Low income parents (less than 10,000 GBP)	35.0%
Medium income parents (between 10,000 – 19,999 GBP)	21.1%
High income parents (more than 20,000 GBP)	20.4%
Respondents who have access to private car	55.4%
Respondents who have children in their household	46.9%
<i>(b) Characteristics of Individual Activity-Travel Engagements</i>	
Number of trips on the day	3.54
- Number of personal trips / day	1.57
- Number of escorting trips / day	0.42
- Number of mixed trips / day	1.55
Daily total travel time (minutes) incl. walking	69.81
- Travel time spent for personal trips (min)	25.42
- Travel time spent for escorting trips (min)	7.23
- Travel time spent for mixed trips (min)	37.16
Total daily travel distance (in tenth miles) incl. walking	202.36
Total activity duration (minutes)	266.99

TABLE 2. Individuals' daily travel time and out-of-home time expenditures

(a) Individual Daily Travel Time (min)

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	71.34	69.33	67.19	71.50	68.99
2	70.30	69.50	68.80	69.52	69.44
3	69.40	67.70	68.75	67.14	80.12
4 or more	70.81	70.46	70.92	65.48	60.28

Incremental travel time changes, compared to households without children (in min):

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	0.00	-2.01	-4.14	0.17	-2.35
2	0.00	-0.80	-1.50	-0.78	-0.86
3	0.00	-1.70	-0.65	-2.27	10.72
4 or more	0.00	-0.35	0.11	-5.33	-10.53

Incremental travel time changes, compared to a-single-person households (in min):

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	0.00	0.00	0.00	0.00	0.00
2	-1.04	0.17	1.61	-1.99	0.46
3	-1.93	-1.62	1.56	-4.37	11.13
4 or more	-0.53	1.13	3.73	-6.02	-8.70

(b) Individual Total Daily Out-of-home Time Expenditure (min)

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	304.99	332.33	319.08	300.12	296.24
2	317.53	356.20	342.61	334.40	317.43
3	369.56	385.54	366.44	339.46	324.38
4 or more	390.70	392.34	346.59	307.27	309.43

Incremental out-of-home time expenditure changes, compared to households without children (in min):

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	0.00	27.35	14.09	-4.87	-8.74
2	0.00	38.67	25.08	16.87	-0.10
3	0.00	15.98	-3.12	-30.10	-45.18
4 or more	0.00	1.64	-44.11	-83.43	-81.27

Incremental travel time changes, compared to a-single-person households (in min):

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	0.00	0.00	0.00	0.00	0.00
2	12.54	23.87	23.52	34.28	21.19
3	64.57	53.20	47.36	39.34	28.13
4 or more	85.71	60.00	27.51	7.15	13.19

TABLE 3. Households' daily travel time and out-of-home time expenditures

(a) Household Daily Travel Time (min)

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	71.34	124.32	169.54	211.56	235.02
2	121.15	174.23	228.41	273.51	315.67
3	163.12	214.71	258.91	303.13	487.53
4 or more	238.33	275.74	312.81	348.13	226.25

Incremental travel time changes, compared to households without children (in min):

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	0.00	+ 52.98	+ 98.2	+ 140.2	+ 163.68
2	0.00	+ 53.08	+ 107.3	+ 152.4	+ 194.52
3	0.00	+ 51.59	+ 95.8	+ 140.0	+ 324.42
4 or more	0.00	+ 37.41	+ 74.5	+ 109.8	-12.08

Incremental travel time changes, compared to a-single-person households (in min):

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	0.00	0.00	0.00	0.00	0.00
2	+ 49.8	+ 49.9	+ 58.9	+ 62.0	+ 80.65
3	+ 91.8	+ 90.4	+ 89.4	+ 91.6	+ 252.51
4 or more	+ 167	+ 151.4	+ 143.3	+ 136.6	-8.77

(b) Household Total Daily Out-of-home Time Expenditure (min)

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	304.99	598.01	829.05	910.03	1098.09
2	560.08	926.81	1165.96	1330.92	1416.43
3	886.45	1257.64	1407.57	1586.10	1923.57
4 or more	1376.35	1564.23	1530.74	1679	1201.06

Incremental out-of-home time expenditure changes, compared to households without children (in min):

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	0.00	+ 293.02	+ 524.06	+ 605.05	+ 793.11
2	0.00	+ 366.73	+ 605.88	+ 770.85	+ 856.35
3	0.00	+ 371.19	+ 521.12	+ 699.65	+ 1037.12
4 or more	0.00	+ 187.88	+ 154.39	+ 302.65	-175.29

Incremental travel time changes, compared to a-single-person households (in min):

No of adults in the household	No of children in the household				
	0	1	2	3	4 or more
1	0.00	0.00	0.00	0.00	0.00
2	+ 255.1	+ 328.8	+ 336.9	+ 420.9	+ 318.34
3	+ 581.5	+ 659.6	+ 578.5	+ 676.1	+ 825.47
4 or more	+ 1071	+ 966.2	+ 701.7	+ 767.0	+ 102.97

TABLE 4. Estimation results of Full Time workers' daily travel time (TT) and out-of-home time (OHT) expenditures according to the Stochastic Frontier model

	FT worker TT (cost frontier)				FT worker OHT (prod. frontier)			
	Excluding out-of home activities		Including out-of home activities		Excluding out-of home activities		Including out-of home activities	
	Coeff.	t-stats	Coeff.	t-stats	Coeff.	t-stats	Coeff.	t-stats
Constant	25.92	6.96	13.63	3.30	502.76	18.60	279.58	11.41
Male	-1.36	-1.89	0.04	0.05	25.94	5.31	10.77	2.44
24 years old or less	2.16	0.58	-0.09	-0.02	145.38	5.46	160.73	6.84
25-44 years old	4.51	1.29	1.98	0.52	119.76	4.75	132.00	5.94
45-64 years old	3.33	0.95	0.32	0.08	99.15	3.93	106.78	4.81
Medium income parents	-1.44	-1.21	-0.99	-0.79	17.80	2.12	16.85	2.26
High income parents	4.28	3.57	3.96	3.18	25.26	3.03	25.13	3.39
Car availability	1.35	1.27	-3.22	-2.80	1.83	0.25	-3.24	-0.48
More than one adult in the household	-1.32	-1.43	-1.13	-1.18	-9.50	-1.51	-8.56	-1.52
One child in the household	-0.32	-0.33	-1.21	-1.14	-26.87	-4.03	-14.50	-2.36
Two children in the household	-0.20	-0.21	-0.85	-0.77	-33.84	-5.02	-22.93	-3.65
Three children in the household	0.21	0.13	-2.14	-1.19	-24.15	-2.12	-14.00	-1.36
Four or more children in the household	-2.65	-0.77	-0.78	-0.22	-4.26	-0.19	-3.54	-0.18
Personal trips			6.77	14.02			115.30	35.35
Escorting trips			5.13	9.07			-4.16	-1.32
Mixed purpose trips			8.07	18.58			-2.60	-1.10
λ	8.12	12.95	5.93	18.06	3.05	28.27	1.92	28.84
σ	54.60	4860	50.43	4836	252.28	4781	191.03	4831
N	3955		3955		3955		3955	
σ_v	6.677		8.384		78.485		88.167	
σ_u	54.192		49.727		239.765		169.462	
Log-likelihood	-19042		-18852		-25632.39		-24949.3	

TABLE 5. Estimation results of Stochastic Frontier of Unemployed travellers' daily travel time (TT) and out-of-home time (OHT) expenditures

	Unemployed TT (cost frontier)				Unemployed OHT (cost frontier)			
	Excluding out-of home activities		Including out-of home activities		Excluding out-of home activities		Including out-of home activities	
	Coeff.	t-stats	Coeff.	t-stats	Coeff.	t-stats	Coeff.	t-stats
Constant	25.19	56.61	15.09	18.33	90.07	27.30	90.23	0.13
Male	0.24	0.70	0.84	1.91	-6.90	-2.66	-0.69	-0.27
24 years old or less	-0.92	-0.88	-0.18	-0.13	74.24	9.44	103.54	13.52
25-44 years old	0.28	0.29	1.53	1.22	4.77	0.66	24.02	3.39
45-64 years old	0.23	0.44	0.25	0.37	6.53	1.67	10.98	2.82
Medium income parents	0.39	0.69	0.19	0.26	2.20	0.51	-3.31	-0.76
High income parents	1.21	1.39	1.83	1.70	10.16	1.59	-5.91	-0.92
Car availability	0.48	1.08	-1.73	-2.92	5.67	1.69	-14.48	-4.14
Another adult in the household	-0.69	-1.84	-1.24	-2.59	-4.28	-1.49	-15.81	-5.55
One child in the household	0.48	0.49	0.60	0.47	4.16	0.58	13.33	1.84
Two children in the household	0.26	0.26	-0.58	-0.45	5.92	0.82	10.45	1.44
Three children in the household	0.79	0.74	-0.50	-0.36	7.44	0.96	6.38	0.82
Four or more children in the household	0.27	0.23	1.16	0.75	-2.96	-0.34	9.37	1.07
Personal trips			3.62	9.99			90.76	43.34
Escorting trips			3.66	12.44			3.67	2.37
Mixed purpose trips			5.65	18.05			41.51	27.21
λ	19.72	9.81	9.84	17.49	3.09	30.25	0.00	0.00
σ	51.90	8583.49	48.82	8575.44	179.78	8611.81	100.90	8519.54
N	6953		6953		6953		6953	
σ_v	2.628		4.935		55.403		0.002	
σ_u	51.834		48.567		171.029		100.9	
Log-likelihood	-32758.4		-32584.5		-42689.4		-41947.90	

TABLE 6. Estimation results of Stochastic Frontier of Part-time Workers' daily travel time (TT) and out-of-home time (OHT) expenditures

	Part-time workers TT (cost frontier)				Part-time workers OHT (cost frontier)			
	Excluding out-of home activities		Including out-of home activities		Excluding out-of home activities		Including out-of home activities	
	Coeff.	t-stats	Coeff.	t-stats	Coeff.	t-stats	Coeff.	t-stats
Constant	26.69	10.23	15.26	4.95	174.92	11.57	66.59	4.23
Male	-0.29	-0.17	0.54	0.32	2.76	0.30	-4.57	-0.55
24 years old or less	5.07	1.56	6.24	1.92	80.51	4.43	83.90	5.23
25-44 years old	5.60	1.99	6.59	2.38	70.81	4.74	69.47	5.23
45-64 years old	4.96	2.18	4.55	2.00	42.75	3.40	38.66	3.46
Medium income parents	-1.01	-0.74	-1.08	-0.78	14.31	1.89	18.62	2.76
High income parents	3.79	1.75	3.27	1.51	22.47	1.89	33.55	3.18
Car availability	0.83	0.54	-4.06	-2.48	3.27	0.37	-8.93	-1.10
Another adult in the household	-0.37	-0.22	0.61	0.37	-6.20	-0.68	-1.33	-0.16
One child in the household	2.18	1.10	-0.38	-0.19	-27.13	-2.51	-13.27	-1.35
Two children in the household	0.29	0.14	-3.44	-1.54	-30.20	-2.66	-19.76	-1.83
Three children in the household	5.14	1.78	0.07	0.02	-55.94	-3.49	-44.30	-2.93
Four or more children in the household	-0.45	-0.09	-7.05	-1.21	-40.28	-1.42	-29.50	-1.15
Personal trips			4.59	5.97			67.13	18.07
Escorting trips			5.40	8.04			7.22	2.31
Mixed purpose trips			5.90	8.28			17.22	4.95
λ	6.74	8.49	5.59	10.62	1.42	14.93	1.62	15.50
σ	50.82	1590.86	47.41	1584.86	160.25	1559.93	148.52	1548.79
N	1301		1301		1301		1301	
σ_v	7.457		8.348		92.36		77.851	
σ_u	50.27		46.67		130.956		126.484	
Log-likelihood	-6192.69		-6129.65		-8082.38		-7936	