INTERPERSONAL COOPERATION IN TOUR-BASED MODE CHOICE: THE ROLE OF HOUSEHOLD RESOURCES AND SPATIAL SETTING

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ABSTRACT

Under social, temporal, spatial and resource constraints, household members interact and search for ways to fulfil household and individual needs, one of which is travelling together. Understanding the motivation for joint household travel and its effect on an individual's mode choices is critical to the formulation of transport policies and planning practices for sustainable transport choices. This paper examines individuals' mode choices with joint household travel being explicitly incorporated within a nested logit model using the Sydney Household Travel Survey data and a typology of tours that captures various patterns of household interactions. The results indicate that joint travel is influenced by household resources, social and mobility constraints, activity types, and the land use patterns at both origin and destination. Also, mode choices differ significantly across joint tour patterns with public transport being less likely to be used for joint travel. Scenario analysis shows that individual tours contribute the most while complex joint tours contribute least to modal shifts from car to public transport which results from changes to transport policies and the level of services. Contrary to suggestions in the literature, a joint household (as compared to individual) travel analysis does not necessarily identify a lower modal shift for policy outcomes.

Keywords: joint travel, mode choice, intra-household interactions, activity-based modelling, land use, public transport, tour typology.

OBJECTIVES

Everyday experience shows that the travel decisions of a household member are not necessarily independent of the travel behaviour of other members of their household and yet interpersonal cooperation is rarely taken into consideration when analysing daily arrangements of activity and travel. Whilst difficult to implement, it is important to incorporate interpersonal interactions explicitly into travel demand models not only for a better understanding of travel behaviour but also for more accurate travel demand forecasting. Research centred on intra-household interactions and group decisions has recently become a particularly active area of research, as seen by special issues of *Transportation* (Bhat and Pendyala, 2005) and *Transportation Research* (Timmermans and Zhang, 2009). However, much remains to be explored and this study aims to inform and contribute to this debate.

Understanding the motivation for joint household travel and the circumstances under which it occurs is important for developing policy and for the planning of public transport and high occupancy vehicle/toll (HOV/HOT) lanes. For instance, if the spatial separation between home and school is the main motivation for chauffeuring children to school, then improved school bus services may reduce traffic congestion and the environmental impacts of school travel. On the other hand, the introduction of HOT lanes or higher tolls will help in raising revenue, but not necessarily reduce congestion, if joint household travel arrangements are the result of time schedule synchronisation of household members' activities or limited household resources.

This study proposes an analysis of individual's tour-based mode choice under social, interpersonal, and spatial constraints. Specifically, the study explores how intra-household interactions, household resources, and the household's spatial setting influence the travel mode of each household member. The travel mode for each home-based tour of all household members is modelled conditioned on joint household decisions, which are identified as patterns of interpersonal cooperation, in arranging daily activities into home-based tours. The research objective is to contribute to the understanding of the role of interpersonal interactions in travel behaviour. Recognising the role of intra-household interactions in travel demand and quantifying the impact of these interactions is an important first step to their inclusion in travel demand models to provide a more credible analysis of travellers' response to policies and changes in land use.

The paper starts with a review of the literature on intra-household interactions focusing on modelling approaches, empirical findings, and limitations. This is followed by a description of data sources and a typology of joint household tours used in this paper. Descriptive and model estimation results are then presented, followed by the model application. The paper concludes with a summary of the main findings and a discussion of the implications for transport policy and planning practice.

LITERATURE REVIEW

Research of interpersonal interactions can be broadly classified into four groups based on the modelling methodology and the choice variable type (Srinivasan and Bhat, 2005; Kang and Scott, 2011). The first approach involves joint estimation of multiple continuous choice variables using either Structural Equations Modelling (SEM) or Seemingly Unrelated Regression (SUR) such as described by Fujii et al. (1999) and Zhang et al. (2005). The second approach is based on discrete choice models and time shares models, such as Scott and Kanaroglou (2002) and Gliebe and Koppelman (2002). The third approach uses a discrete-continuous model system that jointly estimates both discrete and continuous aspects of the choice (e.g., Srinivasan and Bhat, 2006). The final approach is based on micro-simulation including the work of Meister et al. (2005) and Miller et al. (2005). This section provides an overview of these approaches as the more detailed description and example application of each technique is available in the cited references above and elsewhere (Kang and Scott, 2011; Ho and Mulley, 2013a).

From the household decision-making perspective, in each of the methodologies discussed above, the intra-household interactions can be grouped into two major classes. The first class makes use of existing individual decision choice models such as Wen and Koppleman (2000), Scott and Kanaroglou (2002), Rose and Hensher (2004), Vovsha and Petersen (2005), Srinivasan and Bhat (2005; 2006), and Schwanen et al. (2007). The second class explicitly incorporates group decisions into household travel behaviour models using different types of group utility functions, which include the work of Timmermans et al. (1992), Abraham and Hunt (1997), Gliebe and Koppelman (2002; 2005), Meister et al. (2005), Miller et al. (2005), Zhang et al. (2009), and Kato and Matsumoto (2010). The two classes share common features in terms of data requirements and their ability to incorporate and represent heterogeneous intra-household interactions. While the group-based modelling approach can identify the relative influence and hence the power of each household member in the household decision-making, the individual-based modelling approach facilitates model estimations and predictions. Both of these approaches have drawbacks discussed below. The main difference between the two modelling approaches is the incorporation of household interactions and group decision rules in the second class.

The individual-based approach, used in most practical activity-based travel demand modelling systems, classifies intra-household interactions into several components. Due to the complexity of travel behaviour with interpersonal interactions, it is inevitable that the decisions are broken down and modelled in a particular sequence. Typically, five important components of intra-household interactions are considered. These are the coordination of household members' daily activity-travel patterns (e.g., Vovsha et al., 2004; Bradley and Vovsha, 2005), serving household members with restricted mobility by providing drop-offs and pick-ups (e.g., Vovsha and Petersen, 2005; Davidson et al., 2011), engagement in joint household activities (e.g., Scott and Kanaroglou, 2002; Vovsha et al., 2003), sharing household maintenance responsibilities (e.g., Srinivasan and Athuru, 2005; Srinivasan and Bhat, 2005; Schwanen et al., 2007), and the allocation of household cars (e.g., Wen and Koppelman, 2000; Roorda et al., 2009). The main drawback to this approach is the lack of structural linkages between model components and the reliance upon simulation to ensure consistency between household members (Gliebe and Koppelman, 2005).

The group-based approach uses a group utility function to aggregate individual utilities into a household utility. Different group utility functions are used in the literature including multi-linear, iso-elastic, capitulation, autocracy, compromise, maximum, minimum, and Nash-type functions (Zhang et al., 2009). This approach defines alternative utilities with respect to the household as opposed to each individual, although probability expressions for each household member may be preserved (Gliebe and Koppelman, 2002; 2005). The group-based approach typically faces the challenge of representing choices of multiple-person households due to the combinatorial explosion of potential alternatives. Consequently, this approach is more applicable to one-off decisions (such as residential location, household vehicle ownership and daily time use) that have a manageable and tractable number of alternatives. When applied to repeated choices based on a discrete unit of travel, such as daily activity-travel patterns and travel mode, the choice set must be formed in such a way so one chosen alternative exists for each household member while joint household travel outcomes must be consistent among/between household members. This requires active agents to be limited to two household heads and constraints to be imposed on model specification (Gliebe and Koppelman, 2005).

Empirically, intra-household interactions appear to be a relevant factor to decision-making as reflected by the substantial proportion of regional travel which is made jointly (e.g., Vovsha et al., 2003; Kang and Scott, 2008) and the statistically significant influence of household members on household decisions in every empirical study that has identified explicitly a role for individual relative influences (e.g., Gliebe and Koppelman, 2005; Zhang et al., 2009). However, the empirical evidence to date has focused primarily on adult behaviour or a limited set of activities such as maintenance and discretionary journey purposes. In fact, most of these studies use data from activity-travel surveys that often do not collect activity-travel diaries for all household members with children under 15 years old being neglected. Moreover, only a few surveys have collected the companion information (Vovsha et al., 2003; Srinivasan and Bhat, 2008). In practice, too, the intra-household dependencies in activity-travel behaviour have been explored mostly at the top level of activity generation and much less at the lower level of joint household travel arrangements, given that activities have already been generated. This paper thus extends the literature by investigating the role of intra-household interactions in tour-based mode choice with all household members being considered.

A further contribution of this paper is to separate out the role of household resources and the spatial setting on the basis that travel decisions are made under some specific social, temporal, spatial and resource constraints. This contrasts with the existing literature, which has tended to relate intra-household interactions to household and individual characteristics, and activity types. Schwanen et al. (2007) found that the allocation of household tasks between spouses do not take place in a geographical vacuum and land use patterns at the place of residence have a smaller impact than the traveller's socio-demographics. This paper examines the effect of land use patterns at both origin (i.e., home) and destination (or activity location) on joint household travel using micro-level variables. The next section describes data sources and a typology of joint household tours that captures various patterns of intra-household cooperation in daily travel.

DATA AND METHODOLOGY

Travel data: the Sydney Household Travel Survey

The main data used for this analysis are the Sydney Household Travel Survey (HTS), administered by the Bureau of Transport Statistics (BTS). A full description of the data can be found in Ho and Mulley (2013a). For the sake of clarity and cohesion, the main characteristics of the data and the definitions of terms used in this paper are described. The Sydney HTS was first conducted in 1997/98 and has been running continuously since then, with approximately 3,500 households being surveyed annually. Each wave includes a survey of household characteristics, person characteristics and a 24-h travel diary for each participant. All household members are asked to answer a face-to-face interview which increases accuracy. The dataset used in this paper is based on pooling data from the three waves 2007/08, 2008/09 and 2009/10. Only fully responding households were chosen for analysis. Weekend travel is substantially different from weekday analysis and is not considered as part of this paper for space constraint reasons. No sampling weights are used in the descriptive analysis or in the model estimation.

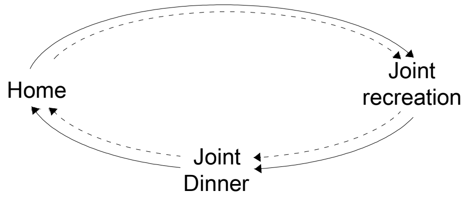
This paper uses the home-based tour as the unit of analysis and identifies joint household tours as patterns of intra-household interactions and spatial-temporal constraints. A home-based tour is a series of trips that start and end at the home (Shiftan, 1998). A small number of tours that began or ended at an out-of-home location were eliminated from the sample due to potential difficulty in interpretation. Each tour is assigned a main purpose based on a hierarchy with work as the highest priority, followed by education, maintenance and discretionary, adapting Stopher et al. (1996). Similarly, for tours involving more than one travel mode, a hierarchy is adopted identifying the main mode as the one most likely to take up the longest part of the tour, especially in time. Public transport is highest on this adopted hierarchy, followed by car and walking. A tour involves multiple trips with each trip being defined as any movement from one place to another and being referred to as a trip segment. A home-based tour is considered to be joint if any trip segment is made jointly with one or more household members.

Definitions and descriptions of nine joint tour patterns, representing nine different ways of arranging household activities and travel into a home-based tour, are provided in Figure 1. Following Gliebe and Koppelman (2005), separate lines are used to represent the travel paths of different household members relevant to the tours. It should be noted that while only two lines (two persons) are used in some patterns for illustration purpose, the fully joint tour patterns (J1), for instance, can be further split according to the travel party size. The process of identifying joint household tour patterns is described in Ho and Mulley (2013a).

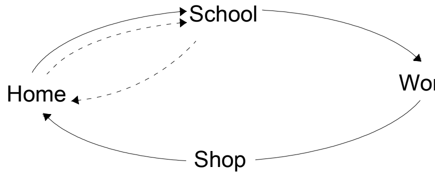
Transport network data: the Sydney Strategic Travel Model

The Sydney HTS data are supplemented with the network data (i.e., level of service data) obtained from the Sydney Strategic Travel Model (STM). This comes from the skim matrices which give estimates of inter-zonal travel times and distances for 2,690 travel zones in Sydney on an average weekday for car mode by four periods of the day (am-peak, inter-peak, pm-peak, and evening) and all public transport combined modes in the am-peak. The skim matrices are available in 5 year intervals from 2006 to 2036 and this study uses data from the year 2006. Technical documentation and standard outputs of the Sydney STM are available on the BTS website (BTS, 2011b).

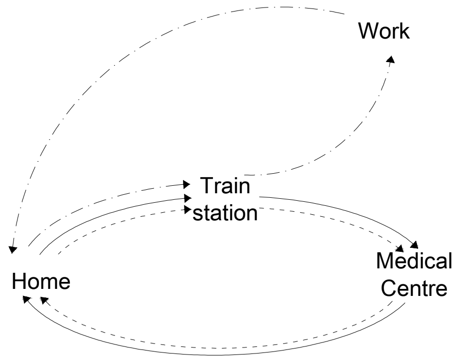
The level of service data for intra-zonal travel are not available from the Sydney STM and are estimated based on individual trip distances recorded in the HTS and an average travel speed of 5 km/h for walking and 30 km/h for car mode (BTS, 2011a). Also, level of service data for public transport for periods of the day other than the am-peak (7:00 - 9:00 am) are not part of the Sydney STM standard outputs. They are estimated by applying multipliers to the public transport level of service during the am-peak using traffic flow and timetable information.



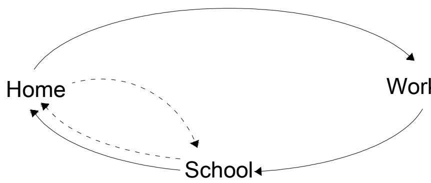
Fully joint tour (J1): a tour pattern in which two or more household members travel together on all trip segments.



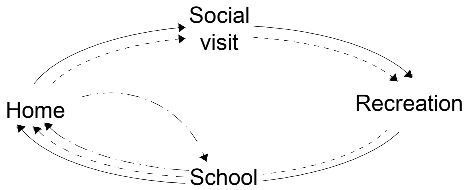
Drop-off tour (J2): a tour pattern in which two household members share rides to an activity location, then go their separate ways and return home separately.



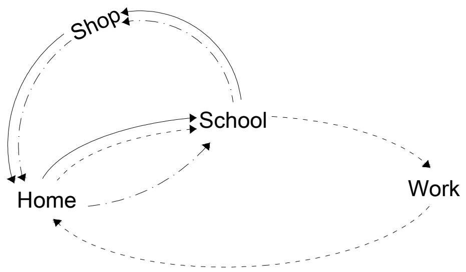
Joint and drop-off tour (J5): a combination of *J1* and *J2* patterns. A travel arrangement in which two household members jointly drop-off a third household member at an activity site or a train station.



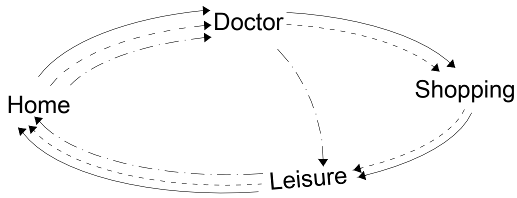
Pick-up tour (J3): a tour pattern in which two household members meet at an out-of-home activity location and return home together.



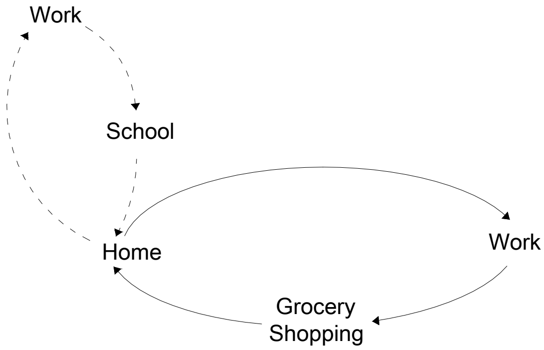
Joint and pick-up tour (J6): a combination of *J1* and *J3* patterns. A travel arrangement where two persons make a fully joint tour and the third person joins in with them at an out-of-home activity location and shares the ride to home. All participants to this tour pattern end their home-based tours together, but not all participants start the tour jointly.



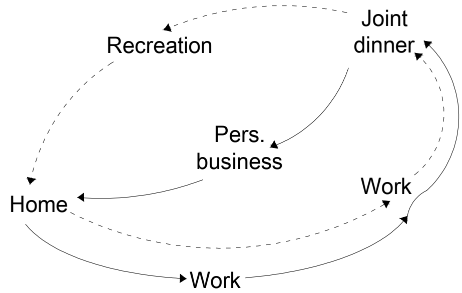
Shared rides tour (J4): a combination of *J2* and *J3* patterns. At least one participant to this tour pattern shares both rides (to and from home) in the same tour with the same or different household members.



Joint and shared rides tour (J7): a combination of *J1* and *J4* patterns. A joint tour pattern in which a household member is dropped off and picked up by other household members.



Individual tour (J9): a tour pattern without any full or partial joint travel with any other household members.



Joint in middle tour (J8): a joint tour pattern in which the participants travel together on some middle part of their home-based tours but leave and return home alone.

Figure 1 - Typology of joint home-based tours (adopted from Ho and Mulley, 2013a)

Land use data

In addition to the HTS and the network data, the Bureau of Transport Statistics provided land use data measured at the micro-level for all individuals and the travel zone level for 2,690 travel zones in Sydney in Geographical Information System (GIS) layers. The micro-level land use data includes walking distance from home, workplace (workers only) and school (students only) to the closest bus stop; walking distance from home to the closest high frequency public transport node, defined as having 12 or more services per hour during the am-peak; distance between home and school, home and workplace, workplace and school, and between workplaces (dual worker households). All of these distance variables are measured at the individual level based on the road network and the real X and Y coordinates of the home, school and workplace.

Other dimensions of land use have been derived from the GIS layers provided. The public transport density is derived from the public transport network layers showing locations of train stations and bus stops, both with their service frequency on a typical working day from 6:00 – 10:00 am. Weighted kernel density is used to capture aspects of public transport design and layout. Tracy et al. (2011) and Ho and Mulley (2013b) provide a detailed process for estimating weighted kernel density and discuss the advantages of this measure over using a measure based on point density.

The travel zone layer showing zone boundaries and centroids with zone attributes, including population and total employment by industry, is used to compute opportunity density and mixed land use. Traditionally, land use mix only considers diversity on the ground (the horizontal component). This study incorporates the opportunities (employment, for example) as part of the land use measure (the vertical component). A combined index, called mixed opportunities per unit area, is defined as:

$$\text{Mixed opportunities per unit area} = \frac{\sum \text{Opportunity}_{it}}{\text{Area}_i} \cdot \left(-\frac{\sum p_{it} \ln(p_{it})}{\ln(n)} \right) \quad (1)$$

where p_{it} is the proportion of opportunities category *t* (retail trade, accommodation and food services, financial and insurance services, education and training, health care and social assistance) within travel zone *i* and *n* (= 5) is the number of opportunity categories. The term in parentheses in this expression is the mean entropy for land uses and is typically used to measure mixed land use (see Cervero and Kockelman, 1997). The advantage of this combined measure is that it reduces the potential for multicollinearity in the model.

To capture aspects of road network design and layout, road link density and pseudo node density are retrieved from the road network GIS layer. The former is a measure of street connectivity and the latter is a proxy for ease of walking. Pseudo nodes are used to identify curvy roads, dead-end streets and roundabouts since the denser the pseudo nodes, the less direct or straight the road is and the less walkable the local area. For road link density the converse is true, the denser the road links the more conducive the local area is to walking and using public transport (Tsai et al., 2012). Travel zones vary widely in terms of geography and local road network and, to resolve issues of the effect of geographical aggregation on the correlation between land uses and mode choice, an 800 m buffer is compared against the travel zone boundary for these measures to choose the better aggregation.

RESULTS

Descriptive analysis

Figure 2 shows a distribution of tours by the joint tour types defined by Figure 1, segmented by travel purpose on an average weekday in Sydney. For all purposes combined, the sample includes 16,522 home-based tours with 48% of these tours being made by individuals. Tours involving joint household include fully joint tours (J1) representing the most important joint tour type (21%) and equal the total of all partially joint tours (J2 – J4) taken together (22%). Vovsha et al. (2003) reported similar findings for fully and partially joint tours in the two metropolitan areas of Mid-Ohio and New York in the USA. Their study, however, is based on a sample of motorised tours only and this explains the lower share of mixed tours (J5-J7) as compared to this evidence from Sydney (3% vs. 9%).

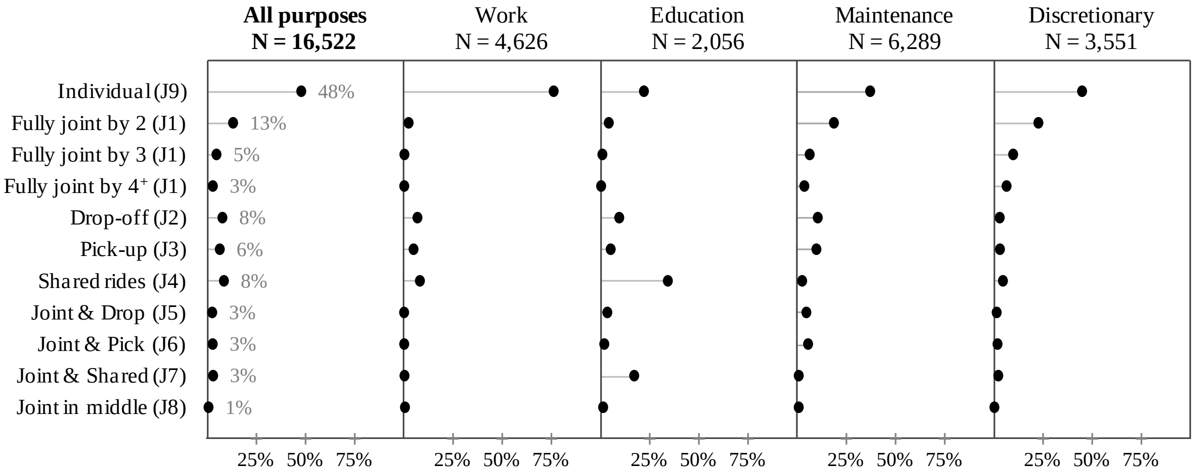


Figure 2 – Distribution of joint household tours by tour main purpose, average weekday in Sydney

The distribution of joint tour patterns differs significantly across activity types. Tours to work and work-related business are mostly individual but partially joint tours (J2-J4) also account for a substantial proportion (20%). Maintenance (shopping, personal business and serving passenger) and discretionary (recreational and social) activities are characterised by a high share of fully joint travel while education (school and childcare) tours are more likely to be chauffeured in both directions. Joint travel to education is not normally followed by a joint activity between the chauffeur and the student, and that school and other activities such as work and serving passenger can be synchronised only for one direction (Vovsha et al., 2003) and this explains the difference noted in the sample. Furthermore, the jointly drop-off and pick-up pattern (J7) accounts for a high portion of education tours suggesting interpersonal constraints and interactions in daily activity and travel. An example for interpersonal constraints is that an infant, who would not be left at home alone, accompanies their mother as she takes a sibling to school. Another example might be that two students, studying at the same school, are being dropped off and picked up on the same car tours.

Figure 3 shows the difference in modal shares for all but one of the joint tour patterns compared to individual tours (J9). The exception is the joint in middle tour pattern (J8) where the difference is not significant at the 5% level using the Chi-squared test. Of all individual tours (the base) made on an average weekday in Sydney, public transport accounts for 16%, car accounts for 67% and walking shares the remaining 17%. Figure 3 shows that the car share increases significantly if tours involve either fully or partially joint travel, and that the more complex the travel pattern the more likely a car is used. Conversely, walking and Public Transport (PT) shares decrease if tours are made jointly with other household members, except for the joint tour patterns involving a drop-off and/or a pick-up (J2 and J4) where PT shares increase over the base. Also, the decrease in PT share is noticeable if travel involves fully joint tours (J1, J6, and J7). These results suggest that PT is not regarded as suitable for fully joint household travel which requires drop-offs and/or pick-ups at either end of the tour. This is, to some extent, explained by the role of intra-household interactions under household resource constraints (e.g., the household car needs to be at home for running household errands) as well as time and space constraints (e.g., train stations are too far to walk, locations of passengers' activities are too far to serve directly) in household travel mode choice.

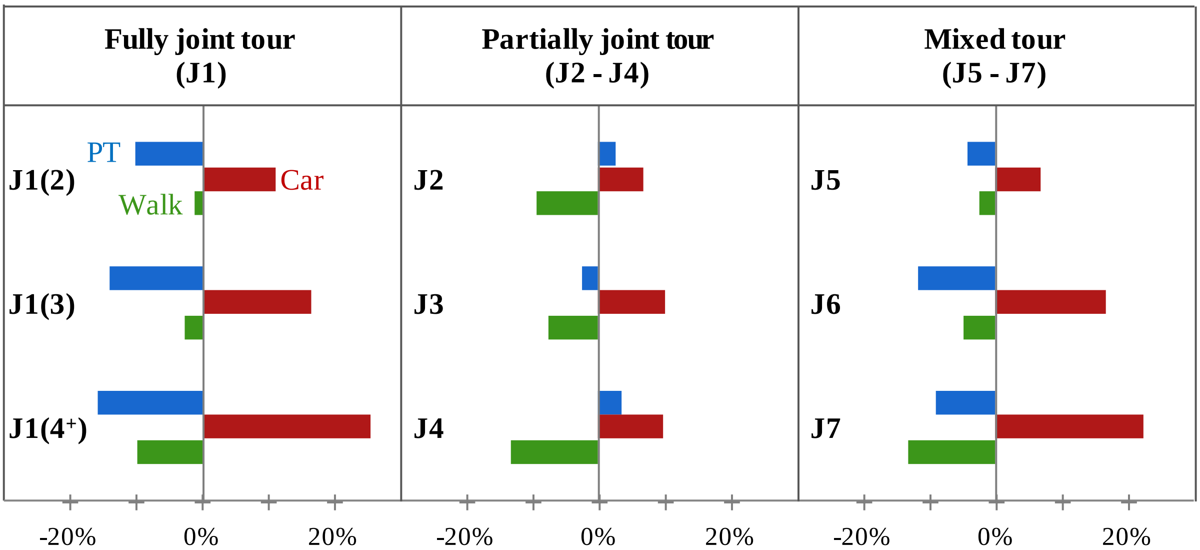


Figure 3 – Difference in modal share for joint tours as compared to individual tours, average weekday in Sydney

Ho and Mulley (2013a) explore the motivation for intra-household interactions in PT use. However, households with different resource constraints may interact differently in the allocation of household resources and the arrangement of household activity and travel. Table 1 compares the median car access distance of car-negotiating households (households with fewer cars than licence holders) with that of car-sufficient households (households with at least as many cars as drivers) for PT tours accessed by car. For PT tours with Park and Ride (P&R), there is no statistical difference between car-negotiating and car-sufficient households. However, for Kiss and Ride (K&R) tours, the median access distance is significantly longer for PT users of car-sufficient households. A possible explanation is that K&R users of car-sufficient households have more opportunities to be dropped off at their most desired station which would otherwise be accessed by P&R if the users hold a driving licence. For PT users without a driving licence, a drop-off at their desired station can be coordinated with another household driver's journey – an option less likely to be available to car-negotiating households.

Table 1 – Median car access distance (in km) by household car ownership and joint tour type

Access distance in km	PT tours with P&R		PT tours with K&R	
	Car-negotiating	**Car-sufficient**	**Car-negotiating**	**Car-sufficient**
Median	5.05	4.71	2.72	3.32
Sample	56	184	193	254
Significant level*	p = 0.542		p = 0.050	

* *Differences in median access distances are tested with the nonparametric median test.*

Modelling approach

Given that joint household travel is sizeable and that modal shares differ significantly across most joint tour types (see Figure 2 and Figure 3 above), this study uses a nested logit model with the upper level capturing joint household travel arrangements and the lower level representing individual's choice of travel mode. The choice structure is shown in Figure 4. At the mode choice stage, it is assumed that activities have already been generated and arranged into home-based tours. It is assumed that the main destination and the required schedule for each tour are known. As is common in the activity-based modelling literature, the assumptions made here include that activities precede mode choice and that the time of travel for main activities is pre-determined (Bradley and Vovsha, 2005; Bradley and Bowman, 2006; Davidson et al., 2011). The upper level can be thought of as a matching model in the sense that household members match their activity agendas to identify possibilities of travelling together for the entire tour or for some trip segments of the tour. Conditioned on the chosen joint household travel arrangement, each household member is then assumed to choose their main travel mode from public transport, car and walking to maximise their personal utility. The observed choice of travel mode for each home-based tour is thus the dependent variable and the individual is the decision-making unit in this model. Therefore, it is not a group decision model *per se*, but rather an individual decision model with joint household travel arrangements being explicitly incorporated.

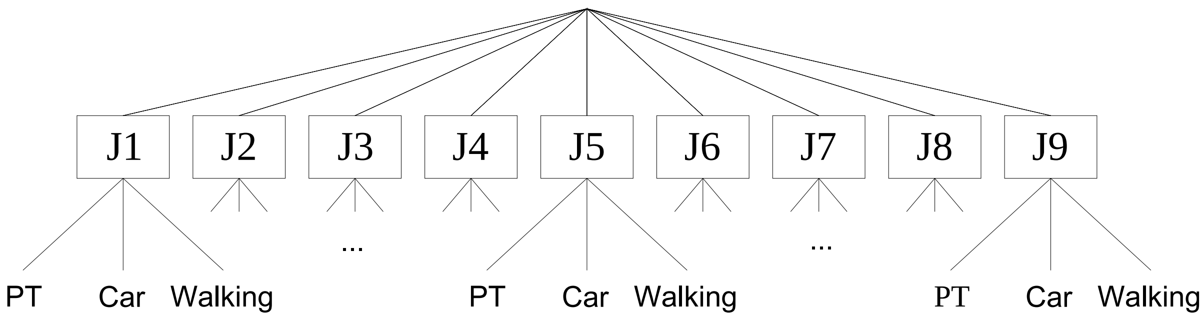


Figure 4 – Choice structure for mode choice model with joint household travel arrangements

The choice structure considers all possible combinations of joint household travel arrangements and tour main modes. The model includes 30 alternatives that correspond to the three tour main modes by ten joint tour types with the fully joint tour pattern (J1) being further split into two separate types: fully joint tour by two household members and by 3^+ household members. Splitting fully joint tours by the travel party size is important for policy implications, such as those relating to HOT lanes, and this is possible with the sample size in the dataset. Not all joint household travel arrangements are available to each household and, in particular, single-person households only have the individual tour pattern (J9) in their choice set. Two-person households, in contrast, have 18 alternatives corresponding to six joint travel patterns (those with a maximum of two participants) and households with 3^+ members have all the identified alternatives in their choice set.

The model specification examines the effect of level of service, transport-related fringe benefits, land use patterns, temporal and spatial synchronisation alongside household, individual characteristics and their interactions. Joint household travel arrangements are assumed to be motivated by household context (e.g., larger households have more opportunities to arrange joint travel), social and mobility constraints (e.g., young children are likely to be escorted) and situational factors (e.g., discretionary activities tend to be pursued jointly). Hence the utility function is specified at the upper level to capture such motivation and constraints. Whether the household can arrange a certain joint travel pattern is also influenced by the household resources, such as car availability and mobility-unrestricted persons, temporal and spatial constraints (e.g., the synchronisation of activity schedules and the spatial separation between locations of household members' activities), the household's spatial setting (e.g., having good public transport services at both origin and destination locations). This is reflected through accessibility or logsum measures entered into the upper level from the mode choice model below.

Model estimation results

All models are estimated using NLOGIT 5.0 and the estimation results are presented in Tables 2 – 5. The logsum parameter for the joint tour pattern J6 was set to one, as the reference, while the logsum parameters for the other tour patterns were estimated freely. Table 2 shows that the logsum parameters lie significantly between zero and one, consistent with random utility maximisation. As alternatives within the same nest are highly substitutable for each other, this partition suggests that decision makers are more likely to substitute their travel mode between car, public transport and walking to carry out a joint travel pattern, as opposed to changing their activity agendas due to the unavailability of a travel mode. From the viewpoint of activity-based travel behaviour, this result is consistent with expectations. McFadden's adjusted Rho-squared is 0.468 indicating a relatively good fit to the data. Compared to the model without land use variables reported in Ho and Mulley (2013a), this model provides better goodness of fit, suggesting the importance of the household's spatial setting in explaining joint household activity-travel arrangements.

Table 2 – Summary statistics and logsum parameters

Summary statistics	
Number of observations	16,522
Number of parameters	107
Log likelihood at convergence	-29,781
Log likelihood at market shares	-35,896
Log likelihood at zeros	-56,195
Mc-Fadden adjusted R-squared (vs. zeros)	0.468
Mc-Fadden adjusted R-squared (vs. constants)	0.167
Logsum parameters*	
Individual tour (J9)	0.656 (10.0)
Joint in the middle tour (J8)	0.420 (5.50)
Fully joint tour by 2 members (J1)	0.653 (5.78)
Fully joint tour by 3^+ members (J1)	0.488 (8.64)
Drop-off tour (J2)	0.468 (13.6)
Pick-up tour (J3)	0.450 (13.5)
Shared ride tour (J4)	0.339 (26.0)
Jointly drop-off tour (J5)	0.407 (9.62)
Jointly pick-up tour (J6)	1.0 (fixed)
Jointly drop-off & pick-up tour (J7)	0.457 (4.64)

* *t-values vs. 1.0 are in parentheses.*

Estimation results for the upper model: joint household travel arrangement

Table 3 shows the estimation results for the arrangement of joint household activities and travel into home-based tours. The joint in the middle tour pattern (J8) was chosen as the reference with its utility being set at zero. Joint household travel arrangements are strongly linked to person type with preschool age children being more likely to accompany adult household members when these adults are giving drop-offs/pick-ups to other household members (shown by the positive coefficients for joint tour patterns J5, J6 and J7). When travelling to participate in an activity, children are more likely to be served in both directions (J4). As children get older, the need for adult supervision and chauffeuring decreases and this is reflected by the decreasing magnitude of coefficients associated with the age of the child for the individual (J9) and shared rides (J4) tours. These findings are consistent with the literature and suggest children at different ages place different constraints on household activity-travel arrangements (Vovsha et al., 2003; Vovsha and Petersen, 2005).

Joint household travel arrangements are significantly associated with activity types with education tours being more likely to be served by other household members and individuals making education tours are more likely to be a drop-off than a pick-up tour. This can be explained by the way in which education and other activities, such as work, can be synchronised more easily for the outbound (drop-off) than inbound (pick-up) as the starting point is the same home location. However, maintenance and discretionary activities are more flexible and show a higher propensity for joint travel and reflect the frame of mind of 'the more the merrier' (see the positive coefficients for joint tour patterns (J1) with a larger value for tours involving 3^+ persons than 2 persons).

Gender differences in household activity-travel arrangements are evident in Table 3 with mothers being more responsible for care-giving and chauffeuring. Also, larger households (with 5^+ persons) exhibit, as might be expected, a greater propensity to arrange joint travel with more people involved (J1(3^+), J5 – J7). Gliebe and Koppelman (2005) and Vovsha et al. (2003) reported similar results although they did not explicitly account for mixed joint tour patterns that represent the typical example of children coming along for a ride.

Table 3 – Estimation results for joint household travel arrangements, average weekday in Sydney 2007-2010*

Variable	Indi-vidual J9	Fully Joint J1(2)	Fully Joint J1(3^+)	Drop off J2	Pick up J3	Shared rides J4	Joint &Drop J5	Joint &Pick J6	Joint& Shared J7
Children aged up to 5	-3.481					0.972	1.487	1.487	1.289
Children aged 6 – 10	-2.964					0.890			1.900
Children aged 11 – 15	-1.366					0.686			1.289
Education tour	-0.653			0.593					
Maintenance tour		2.621	3.563	1.476	1.457				
Discretionary tour		2.692	4.014						
Mother of mix aged children (aged 0-5 & 6-16)			0.677				2.685	2.685	
Household w/ 5^+ persons			0.181				0.697	0.697	0.697
Constant	4.446	0.958	-.060†	0.912	0.813	2.282	0.846	0.896	0.740

** All parameters are significant at the 5% level or better unless otherwise indicated.*
† Not significant at the 10% level.

Estimation results for the lower model: individual's mode choice

Coefficient estimates for the variables explaining the individuals' mode choice are shown in Table 4 and Table 5. No constants were specified for the car mode as this is the reference for each joint tour type. Coefficients associated with the level of service variables are well estimated and do not need to be constrained. Tour-based value of travel time savings (VOT) can be computed from these coefficients. In 2008 Australian dollars, in-vehicle time, wait time and walk time are valued at $6.77, $12.84, and $15.19 per person hour respectively. The absolute values are consistent with empirical evidence of Australian VOT and national guidelines (ATC, 2006; Hensher et al., 2011; Litman, 2011). The implied multipliers for walk and wait times relative to in-vehicle time are also consistent with international evidence (Kato et al., 2010; Abrantes and Wardman, 2011).

Table 4 – Estimation results for mode choice of all joint tour types, Sydney average weekday 2007 – 2010[*]

Variable	**Indi-vidual J9**	**Fully joint J1(2)**	**Fully joint J1(3[+])**	**Drop off J2**	**Pick up J3**	**Shared rides J4**	**Joint &Drop J5**	**Joint &Pick J6**	**Joint & Shared J7**	**Joint in middle J8**
Travel cost (2008 AU$), generic	-0.078	-0.078	-0.078	-0.078	-0.078	-0.078	-0.078	-0.078	-0.078	-0.078
In-vehicle-time (minute), generic	-0.009	-0.009	-0.009	-0.009	-0.009	-0.009	-0.009	-0.009	-0.009	-0.009
Walk time (minute), generic	-0.020	-0.020	-0.020	-0.020	-0.020	-0.020	-0.020	-0.020	-0.020	-0.020
Wait time (minute), generic	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017
Public transport										
No-car household	1.204	1.065								
Worker in car-negotiating HH				0.737	0.788	0.232				
Household income >AU$67,600		-0.453		0.183[§]						
Student over 15 years old	0.257				0.569	0.354				
Flexible working hours	0.543			0.543						
PT fare provided	0.602									
Free parking provided	-0.665			-.308[§]						
Fuel cost provided	-1.643									
Constant	-0.289	-0.907	-1.528	.187[§]	.071[†]	-0.327	-0.306	-2.501	-0.818	.130[†]
Walking										
No-car household	1.045			0.581	0.581	0.581				
Car-negotiating household							0.392	0.392	0.392	
Household income >AU$67,600					-0.291	-.205[§]				
Constant	0.528	0.816	0.156	1.155	0.958	.007[†]	0.284	-0.317	-0.612	.138[†]
Car										
Synchronisation of work and school [a]				0.810		0.816				
Detour to work (km) [a]				-0.030						
Student over 15 years old		-0.263	-0.263							
Licence holder		0.366		1.173	1.228	-0.256			-0.639	

[*] *All parameters are significant at the 5% level or better unless otherwise indicated.* [†] *Not significant at the 10% level;* [§] *Not significant at the 5% level.*
[a] *Applied only to work tours of workers in the household that has at least one student going to school on the same day .*

Table 5 – Estimation results for mode choice (cont'd): effect of land use patterns*

Variable	Indi-vidual J9	Fully Joint J1(2)	Drop off J2	Pick up J3	Shared rides J4
Public transport					
Mixed opportunities per unit area ('000s/km^2), Destination		0.030	0.021	0.021	0.021
Distance from home to closest high freq. bus stop (km)	-0.027		-0.102		
Distance from home to workplace (km)			0.018		0.836
Distance from home to school (km)			0.019	0.019	0.019
Road link density ('000s/km^2), Destination†			1.249	1.243	
Walking					
Mixed opportunities per unit area ('000s/km^2), Origin		0.060			
Road link density ('000s/km^2), Origin†	2.605			1.844	
Pseudo nodes density ('000s/km^2), Origin§	-0.041	-0.217	-0.247		

**All parameters are significant at the 5% level or better unless otherwise indicated.*
† Measured at the travel zone level; §Measured with the 800 m buffer around the travel zone centroid.

Household car ownership is shown as a barrier to PT use in Table 4 with no-car households being more likely than car-owning households to use PT, even for fully joint travel. Also, workers in car-negotiating households use PT significantly more than workers in car-sufficient households (the base) and they do so with a drop-off and/or a pick-up being arranged (see positive coefficients associated with workers in car-negotiating households for partially joint tours in Table 4). This is probably to free the family car for the non-worker in the household to carry out household 'errands'. In comparison, non-workers in car-negotiating households use the car as much as their counterparts in car-sufficient households (corresponding parameters are not significant and are removed from the model). Intra-household interactions are also evident in the travel arrangements of workers in the time synchronisation between work and school activities. Workers are more likely to commute by car and combine commuting with chauffeuring children to/from school if their work time synchronises with the school time of a student in the household. However, the propensity for workers to drop off students at school decreases as the detour distance to serve students increases. The detour distance has an insignificant effect on pick-up decisions indicating the greater time pressure that workers experience at the start of the day as compared to the end (Vovsha and Petersen, 2005).

The barriers to, and motivation, for PT use appears highly associated with transport-related benefits provided to the worker. The propensity to commute by PT increases if the worker has flexible work time or if PT fares are provided by the employer. Conversely, workers are more likely to be car commuters if benefits favour the running of a car. Holding a driving licence increases the propensity of providing drop-off and pick-up but decreases the tendency of undertaking both drop-off and pick-up in the same tour (J4 and J7). This indicates that drivers are more likely to return home in between and forming two separate tours.

Land use, captured by the mixed opportunities per unit area, exhibits a strong influence on mode choice for a number of joint travel patterns. This measure of land use patterns is highly correlated with rail kernel density at the destination (r = 0.73) and so the effect of opportunity density on PT use is partly attributed to rail coverage at the destination (not included in the model due to multicollinearity reasons). But rail kernel density at the origin is largely insignificant on its own in the model without mixed opportunities per unit area. Together these suggest that having good rail coverage at the destination may be more important to PT users than good coverage at their place of residence where access to a train station can be by K&R or P&R. In contrast, a high frequency serviced bus stop close to home increases PT use and a good mix of opportunities at the origin, around the place of residence, increases walking for joint activities. Walking is also influenced by street layout, with more curvy roads reducing walking, while highly connected roads increasing walking as expected but these results are conditioned by the level of aggregation. Road link density is more significant at the travel zone level whilst pseudo node density is better aggregated using a walking distance based buffer. As a majority (80%) of the travel zones have areas smaller than the buffer area (2 km^2), this suggests that a broad area is needed to capture the street layout in terms of cul-de-sacs, roundabouts and curvy roads with pseudo nodes.

Model application and parallel analysis

The estimated model is used next to perform 'what-if' scenarios including changes to policies and level of services. Figure 5 shows the estimation of modal shift resulting from a 50% reduction in PT fares (-50% PT fare), a 20% cut of in-vehicle travel time for PT (-20% PT time), providing all workers with PT fares (Fare provided), taking away free parking lots (No free parking), or allowing all workers to have flexible work hours (Flex hours). With the half fare scenario, for instance, the model predicts that the PT share increases by 2.7% while the car and walking shares decrease by 2.5% and 0.2% respectively. For all scenarios, individual tours contribute the most while complex tours (fully joint and mixed tours) contribute the least to modal shifts. This finding is expected as using a household car for joint household travel is still cheaper than using PT mode so the benefit of the lower fare policy on mode choice will accrue most to individual travel. Similarly, the effect of transport-related fringe benefits on mode choice is noticeable but only for individual tours and, to a lesser extent, partially joint tours.

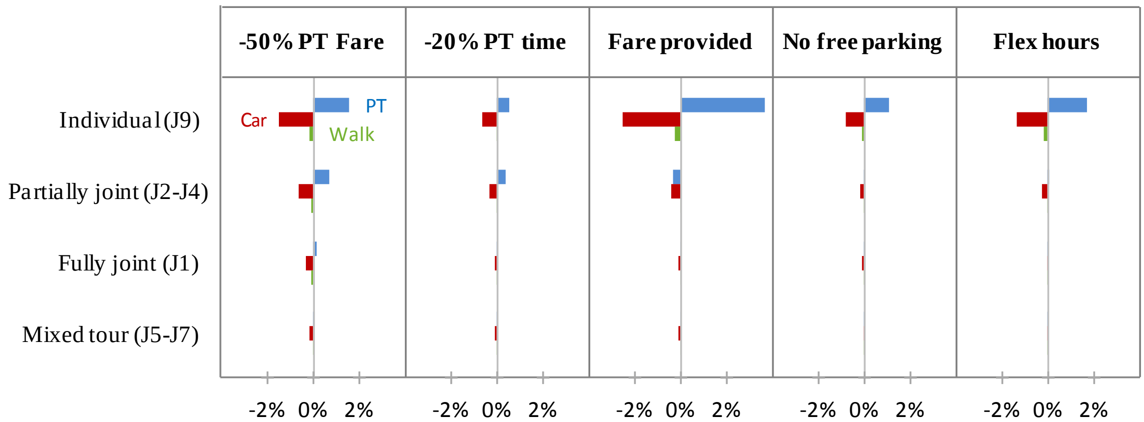


Figure 5 – Estimated modal shift for changes to policies and level of services

Given the substantial differences between individual and joint travel responses to the scenarios shown in Figure 5, it is important for planners and policy-makers to know how sizeable the over- or under-estimation of modal shift would be if joint household travel is not taken into account. This involves the development of an equivalent mode choice model without the joint household travel dimension before applying the same scenarios, and then a comparison of the simulation outcomes. The adopted model without joint household travel takes the form of trinary mode choice (PT, car, walking) and is estimated using the 'artificial tree structure' mechanism to combine mode choice for work, education, maintenance, and discretionary tours in a single model (for more information, see Ho and Mulley, 2013b).

Table 6 compares the simulation results of these two models. For the scenarios with improved PT level of services (the first two columns) the model without joint household travel produces a *lower* estimated modal shift from the car to PT than the model with joint household travel does. This is counter-intuitive as the literature suggests the model without joint household travel to produce a higher modal shift (Gupta and Vovsha, 2013). However, two reasons can explain this difference. First, the model without joint household travel combines all tour types together and, therefore, ignores the benefits of using a car over the PT for joint travel. For these models, the difference between using a car and PT in terms of time, cost and other attributes arising from joint travel will reside in the model error terms and/or by affecting other variables suggesting the model without joint travel will have biased parameters from, for example, omitted variables. Moreover, as the model without joint travel is less sensitive to time, cost and variables that relate particularly to joint travel, changes to these attributes can result in a lower estimated modal shift as compared to the model with joint travel. Second, the estimation of modal shift is aggregated over the sample/population which is affected by the change (the targeted market) but is positively correlated with it. Since the model without joint travel does not separate the different types of tours, it will have a spuriously larger affected market size than the model with joint travel for the last three scenarios shown in Table 6. These two factors offset each other in identifying the level of under- or over-estimation of modal shift if joint travel is not taken into consideration.

Table 6 - Estimation of modal shifts for different scenarios using models with and without joint household travel (without joint household travel in round brackets)

Modal shift *	**-50% PT Fare**	**-20% PT time**	**PT Fare provided**	**No free parking**	**Flexible work hours**
PT [13.0%]	2.7% (1.4%)	1.1% (0.9%)	3.4% (4.1%)	0.9% (0.7%)	1.8% (1.6%)
Car [73.3%]	-2.5% (-1.3%)	-1.1% (-0.9%)	-3.1% (-3.8%)	-0.8% (-0.7%)	-1.7% (-1.5%)
Walk [13.7%]	-0.2% (-0.1%)	0.0% (0.0%)	-0.3% (-0.3%)	-0.1% (0.0%)	-0.1% (-0.1%)
Alternatives affected	All (all)	All (all)	Individual (all) work tours	J9, J2 (all) work tours†	J9, J2 (all) work tours†

* *Values in square parentheses are base market shares of the corresponding mode.* † *J2 = drop-off tour, J9 = individual tour.*

DISCUSSION AND CONCLUSIONS

This paper adds to the understanding of how joint household travel influences travel mode choices and explores how the motivation and needs for the daily arrangements of joint household travel under social, temporal, spatial and resource constraints are incorporated in joint tours. The paper proposes a modelling approach based on the 3 years pooled Sydney Household Travel Survey data and a typology of tours that captures various patterns of intra-household cooperation in daily travel. In Sydney, on an average weekday, joint household travel accounts for more than half of all home-based tours with a sizeable impact on mode choice with more complex joint travel patterns increasing car use. Joint household travel arrangements are found to be affected by resource limitation (fewer cars than drivers), social and mobility constraints (very young children who neither travel individually nor stay home alone), temporal synchronisation and spatial separation of household members' activities, and the household's spatial setting (access to good public transport services and local facilities). In addition, the mode choices arising from different joint tour patterns are found to be influenced by street layout and mix of land uses, level of services, household and individual characteristics, and transport-related fringe benefits provided to the worker.

Explicit modelling of intra-household interactions is motivated by gaining a better understanding of travel behaviour and a more realistic analysis of travellers' response to transport policies, as shown in this paper. The scenario with lower fares for public transport shows that the modal shift from the car to the public transport mode in a model with joint travel gives different responses to those of models without joint travel. Using parallel analysis and scenario simulation, this paper shows that the better behavioural underpinning of a modelling approach, including joint travel, suggests the effect on mode choice of improved public transport services and changes to employer-based policies accrues to individual travel only. Whether modelling without joint travel overestimates or underestimates the mode shift response depends on the way the effect of a spuriously larger affected market offsets the reduced sensitivity of the model to the change.

In spite of the growing efforts to make the use of public transport easier and cheaper, the existence of joint household travel with user preferences travelling by car will continue to be a barrier to increasing public transport ridership. Whether the extension of public transport fare 'deals' aiming at joint travel, such as the Family Funday Sunday ticket scheme in Sydney, will provide public transport with the competitive edge to compete with the car in tours involving joint travel is open to question and requires further research (NSW, 2012).

More insights into joint household travel and associated policy implications could be gained by improvements to the modelling framework to take account of individual preference heterogeneity and the state dependence of multiple tours undertaken by each person. Another natural extension of this research would be to include analysis within an activity-based framework which accommodates explicitly interrelated behaviour of individuals within a household to provide further evidence supporting transport policy formulation and planning practice.

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REFERENCES

Abraham, J. and Hunt, J. (1997) Specification and estimation of nested logit model of home, workplaces, and commuter mode choices by multiple-worker households. *Transportation Research Record,* 1606, 17-24.

Abrantes, P. A. L. and Wardman, M. R. (2011) Meta-analysis of UK values of travel time: an update. *Transportation Research Part A: Policy and Practice,* 45, 1-17.

ATC (2006) *National guidelines for transport system management in Australia.* Australian Transport Council.

Bhat, C. R. and Pendyala, R. M. (2005) Modeling Intra-household interactions and group decision-making. *Transportation,* 32, 443-448.

Bradley, M. and Bowman, J. (2006) SACSIM/05 Activity-based travel forecasting model for SACOG: Featuring DAYSIM – the person day activity and travel simulator. Technical memo number 4: mode choice models.

Bradley, M. and Vovsha, P. (2005) A model for joint choice of daily activity pattern types of household members. *Transportation,* 32, 545-571.

BTS (2011a) 2009/10 Household travel survey summary report. *BTS, NSW Government*.

BTS (2011b) Sydney strategic travel model (STM): Modelling future travel patterns. *BTS, NWS Government*.

Cervero, R. and Kockelman, K. (1997) Travel demand and the 3Ds: density, diversity, and design. *Transportation Research Part D: Transport and Environment,* 2, 199-219.

Davidson, B., Vovsha, P. and Freedman, J. (2011) New advancements in activity-based models. *Australasian Transport Research Forum*, Adelaide, Australia, 28 - 30 September.

Fujii, S., Kitamura, R. and Kishizawa, K. (1999) Analysis of individuals' joint-activity engagement using a model system of activity-travel behavior and time use. *Transportation Research Record,* 1676, 11-19.

Gliebe, J. P. and Koppelman, F. S. (2002) A Model of joint activity participation between household members. *Transportation,* 29, 49-72.

Gliebe, J. P. and Koppelman, F. S. (2005) Modeling Household activity–travel interactions as parallel constrained choices. *Transportation,* 32, 449-471.

Gupta, S. and Vovsha, P. (2013) A model for work activity schedules with synchronization for multiple-worker households. *Paper presented to 92nd Annual Meeting of the Transportation Research Board*, Washington, D.C., 13-17 January 2013.

Hensher, D. A., Greene, W. H. and Li, Z. (2011) Embedding risk attitude and decision weights in non-linear logit to accommodate time variability in the value of expected travel time savings. *Transportation Research Part B: Methodological,* 45, 954-972.

Ho, C. and Mulley, C. (2013a) Incorporating Intra-household interactions into a tour-based model of public transport use in car-negotiating households. *Paper presented to 92nd Annual Meeting of the Transportation Research Board*, Washington, D.C., 13-17 January 2013.

Ho, C. and Mulley, C. (2013b) Multiple purposes at single destination: a key to a better understanding of the relationship between tour complexity and mode choice. *Transportation Research Part A: Policy and Practice*, 49, 206-219.

Kang, H. and Scott, D. (2008) An integrated spatio-temporal GIS toolkit for exploring intra-household interactions. *Transportation,* 35, 253-268.

Kang, H. and Scott, D. (2011) Impact of different criteria for identifying intra-household interactions: a case study of household time allocation. *Transportation,* 38, 81-99.

Kato, H., Tanishita, M. and Matsuzaki, T. (2010) Meta-analysis of value of travel time savings: evidence from Japan. *12th WCTR*, Lisbon, Portugal, 11-15 July.

Litman, T. (2011) Valuing transit service quality improvements: considering comfort and convenience in transport project evaluation. Retrieved: 02/07/2012, from http://www.vtpi.org/traveltime.pdf.

Meister, K., Frick, M. and Axhausen, K. W. (2005) A GA-based household scheduler. *Transportation,* 32, 473-494.

Miller, E. J., Roorda, M. J. and Carrasco, J. A. (2005) A tour-based model of travel mode choice. *Transportation,* 32, 399-422.
NSW (2012) New South Wales Transportinfo. Retrieved: 12/03/2012, from http://www.131500.com.au/tickets.
Roorda, M. J., Carrasco, J. A. and Miller, E. J. (2009) An integrated model of vehicle transactions, activity scheduling and mode choice. *Transportation Research Part B: Methodological,* 43, 217-229.
Rose, J. and Hensher, D. A. (2004) Modelling agent interdependency in group decision making. *Transportation Research Part E: Logistics and Transportation Review,* 40, 63-79.
Schwanen, T., Ettema, D. and Timmermans, H. (2007) If you pick up the children, I'll do the groceries: spatial differences in between-partner interactions in out-of-home household activities. *Environment and Planning A,* 39, 2754-2773.
Scott, D. M. and Kanaroglou, P. S. (2002) An Activity-episode generation model that captures interactions between household heads: development and empirical analysis. *Transportation Research Part B: Methodological,* 36, 875-896.
Shiftan, Y. (1998) Practical approach to model trip chaining. *Transportation Research Record: Journal of the Transportation Research Board,* 1645, 17-23.
Srinivasan, K. K. and Athuru, S. R. (2005) Analysis of within-household effects and between-household differences in maintenance activity allocation. *Transportation,* 32, 495-521.
Srinivasan, S. and Bhat, C. R. (2005) Modeling household interactions in daily in-home and out-of-home maintenance activity participation. *Transportation,* 32, 523-544.
Srinivasan, S. and Bhat, C. R. (2006) A multiple discrete-continuous model for independent- and joint-discretionary-activity participation decisions. *Transportation,* 33, 497-515.
Srinivasan, S. and Bhat, C. (2008) An exploratory analysis of joint-activity participation characteristics using the American time use survey. *Transportation,* 35, 301-327.
Stopher, P. R., Hartgen, D. T. and Li, Y. (1996) Smart: simulation model for activities, resources and travel. *Transportation,* 23, 293-312.
Tsai, C., Mulley, C. and Clifton, G. (2012) The spatial interactions between public transport demand and land use characteristics in the Sydney Greater Metropolitan Area. *Australasian Transport Research Forum 2012*, Perth, Australia, 26 – 28 September 2012.
Timmermans, H., Borgers, A., van Dijk, J. and Oppewal, H. (1992) Residential choice behaviour of dual earner households: a decompositional joint choice model. *Environment and Planning A,* 24, 517-533.
Timmermans, H. and Zhang, J. (2009) Modeling household activity travel behavior: examples of state of the art modeling approaches and research agenda. *Transportation Research Part B: Methodological,* 43, 187-190.
Tracy, A., Su, P., Sadek, A. and Wang, Q. (2011) Assessing the Impact of the built environment on travel behavior: a case study of Buffalo, New York. *Transportation,* 38, 663-678.
Vovsha, P., Petersen, E. and Donnelly, R. (2003) Explicit modeling of joint travel by household members: statistical evidence and applied approach. *Transportation Research Record,* 1831, 1-10.
Vovsha, P., Petersen, E. and Donnelly, R. (2004) Impact of intrahousehold interactions on individual daily activity-travel patterns. *Transportation Research Record,* 1898, 87-97.
Vovsha, P. and Petersen, E. (2005) Escorting children to school: statistical analysis and applied modeling approach. *Transportation Research Record,* 1921, 131-140.
Wen, C.-H. and Koppelman, F. (2000) A conceptual and methodological framework for the generation of activity-travel patterns. *Transportation,* 27, 5-23.
Zhang, J., Timmermans, H. and Borgers, A. (2005) A Model of household task allocation and time use. *Transportation Research Part B: Methodological,* 39, 81-95.
Zhang, J., Kuwano, M., Lee, B. and Fujiwara, A. (2009) Modeling household discrete choice behavior incorporating heterogeneous group decision-making mechanisms. *Transportation Research Part B: Methodological,* 43, 230-250.