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Tour-based mode choice of joint household travel patterns on weekend and weekday

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Abstract Joint household travel, with or without joint participation in an activity, constitutes a fundamental aspect in modelling activity-based travel behaviour. This paper examines joint household travel arrangements and mode choices using a utility maximising approach. An individual tour-based mode choice model is formulated contingent on the choice of joint tour patterns where joint household activities and shared ride arrangements are recognised as part of the joint household decision-making that influences the travel modes of each household member. Two models, one for weekend and one for weekday, are estimated using empirical data from the Sydney Household Travel Survey. The results show that weekend travel is characterised by a high joint household activity participation rate while weekday travel is distinguished by more intra-household shared ride arrangements. The arrangements of joint household travel are highly associated with travel purpose, social and mobility constraints and household resources. On weekends, public transport is mainly used by captive users (i.e., no-car households and students) and its share is about half of that on weekdays. Also, the value of travel time savings (VOTs) are found to be higher on weekends than on weekdays, running entirely counter to the common belief that weekend VOTs are lower than weekday VOTs. This paper highlights the importance of studying joint household travel and using different transport management measures for alleviating traffic congestion on weekdays and weekends.

Keywords Mode choice · Joint travel · Weekend travel · VOT · Intra-household interactions · Activity-based modelling

Introduction

A recognition that travel decisions of a household member are not made in isolation of the household context has produced an interest in intra-household interactions and group decision-making. Intra-household interactions can be observed not only in long term

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decisions such as residential location and vehicle ownership but also in short term decisions including activity participation and vehicle allocation. This study focuses on travel mode choice but incorporates intra-household interactions in short-term activity-travel decisions. Incorporating intra-household interactions in travel demand modelling is an important research area yet remains largely unexplored.

The complex nature of inter-personal interactions has led a number of previous studies to undertake simulation so as to avoid the need of analytical tractability (Miller et al. 2005; Roorda et al. 2006; Roorda et al. 2009). The downside of these studies has been that the computational burden associated with model parameter estimation and an assumed decision-making process which are discussed further in the next section. Of studies using random utility, the intra-household dependencies in activity-travel behaviour have mostly been explored at the top level of activity generation and much less at the lower level of joint household travel arrangement and individual mode choice, given that activities have already been generated. The existing literature tends to approach intra-household interactions by identifying and modelling a limited set of typical household activity-travel patterns such as those between the two household heads, between parents and children or between work and non-work activities (Scott and Kanaroglou 2002; Gliebe and Koppelman 2005). Thus the literature lacks an analytical approach to modelling which permits a variety of different activity-travel patterns amongst all household members together with intra-household interactions. Moreover, the literature has not generally distinguished, within the same geographical area, activity-travel patterns of weekdays and weekends. Where comparisons have existed, it has been limited to analysis of travel purpose with weekend travel patterns dominated by non-work, non-education activities and with the car passenger mode accounting for a higher share on weekends than on weekdays (Lockwood et al. 2005).

This paper builds on these previous studies and draws together behavioural and practical aspects of modelling individual tour-based mode choice with intra-household interactions. The paper uses a typology of joint household tours which allows various patterns of joint household activities and shared ride arrangements to be captured and embedded in the activity-based modelling framework for a better understanding of travel behaviour during weekdays and weekends for more accurate travel demand forecasting in the future.

The rest of the paper is structured as follows. The next section reviews studies which have focused on modelling discrete choices in short-term activity-travel decisions and joint household travel on weekends and weekdays as these provide the context for this paper. This is followed by a description of data sources and a typology of joint household tours. Differences between weekend and weekday activity-travel patterns are then quantified, with a focus on joint household activities and modes of travel. The penultimate section discusses the model structure and the estimation results. The paper ends with concluding remarks and directions for further research.

Household interactions in short-term decisions

As identified in the previous section, there are limited examples modelling intra-household interactions in travel mode choice in the literature, although joint household travel forms an important part in activity-based travel demand models. Explicit incorporation of joint household activities and shared rides may improve the behavioural realism of mode choice models but requires increased complexity and raises issues of tractability and manageability in the analytical approach.

A modelling approach undertaken by Miller et al. (2005) and Roorda et al. (2006) attempted to avoid tractability issues using simulation to examine household interactions in tour-based mode choices. Their mode choice model explicitly incorporates household interactions through vehicle allocation and joint household travel arrangement within the following process. Their three-step modelling process starts with the mode choice for both individual and fully joint tours which are determined without regard for the availability of household cars. Second, it is then decided which household member uses the car if conflicts occur in which more than one household member wants to use the same car at the same time. Finally, whether serve-passenger (ridesharing) opportunities exist within the household is evaluated in terms of total household utility. Implicit in this model is the assumption that an individual's mode choice decisions come first, then joint household travel decisions. However, it may be the case that the decision hierarchy is actually the other way around with household members choosing their travel modes conditional on the joint household travel arrangements. A limitation of the Miller et al. (2005) and Roorda et al. (2006) simulation approach is that serve-passenger travel is considered only being made by car and allocated directly to the passenger's activity: this assumption ignores all household shared ride arrangements by walking (e.g., walking a child to school) and the portion of shared rides by car to a train station (as opposed to the passenger's activity).

Recent advances in modelling intra-household interactions include the development and application of escorting models within an activity-based modelling framework (Vovsha and Petersen 2005; Yarlagadda and Srinivasan 2008; Davidson et al. 2011). The escorting model takes the form of nested logit and divides school tours into two half-tours (outbound and inbound) with each half-tour considering three travel options (pure escort, ridesharing and no escort) and a maximum of three household chauffeurs. The practical application of the model has employed a decision rule of ordering household children by age and modelling their school tours sequentially (Davidson et al. 2011). Variables found to have a significant influence on the escorting decision include chauffeur characteristics (employment status, age, flexibility at work), the child's age, household characteristics and relative distances between home, school and workplace (Vovsha and Petersen 2005; Yarlagadda and Srinivasan 2008).

Existing research of intra-household interactions have mostly focussed on daily activity-travel pattern (DAP), joint activity generation, and allocation of maintenance activities amongst household members. From the time use perspective, Srinivasan and Bhat (2006) developed a multiple discrete- continuous choices model to investigate the interdependencies of discretionary activity participation and duration choices amongst married couples in households with at least one employed adult with all children (where present) being under 16 years old. Their model simultaneously determines five inter-related activity participation and duration choices including two in-home solo activities (one for male and one for female), two out-of-home solo activities and an out-of-home joint activity. Intra- and inter-personal tradeoffs between in-home and out-of-home activities, and between solo and joint activities are represented using an error correlation structure. They found that activity pattern of the individual impacts on their spouse's (or partner's) discretionary activity patterns and the decision to pursue activities jointly.

Bradley and Vovsha (2005) studied coordination between household members in choosing their DAPs by classifying a day-activity into three patterns (mandatory, non-mandatory, and home) and household members into eight person types (full-time worker, part-time worker, university student, non-worker, retired, driving-age children, pre-driving age children, and pre-school age children). Intra-household interactions are explicitly incorporated through pair-wise and triple-wise interaction terms in a joint choice model of

DAPs which can simultaneously treat all possible combinations of individual DAPs for up to five household members. Gliebe and Koppelman (2005) developed a parallel choice constrained logit (PCCL) model to investigate interactions between household heads. Their model is unique in its capacity to maintain separate probability expressions for each of the two household heads while the weighted sum of their expected utility represents the total utility to be derived by a whole household. Also, the PCCL model allows the impacts of contextual and situational factors on household interactions to be modelled explicitly. A common element to these studies is that the choice model structure becomes increasingly complex very quickly as well as being sensitive to household size and the number of basic DAPs considered and in turn this requires specification constraints to overcome estimation and management issues (Bradley and Vovsha 2005; Gliebe and Koppelman 2005). These studies have also focussed on joint household activity-travel mostly for weekday travel and much less on weekend day.

Liu (2009) provided a comprehensive review of weekend activity and travel patterns. Among the scarce but growing literature on weekend mode choice modelling, a few studies exist to offer evidence on the prevalence of weekend joint household travel and its effect on mode choice. Lockwood et al. (2005) using US data, found the shared-ride mode accounted for 48 % of total trips on weekends, compared to 32 % on weekdays. Similarly, O'Fallon and Sullivan (2003) found in New Zealand that the car passenger mode accounted for a higher share on weekends than on weekdays, and that average car occupancy increased from 1.5 on weekdays to 1.8 on weekends. Yagi et al. (2011) found in Indonesia that the propensity to undertake fully joint household tours is much higher on weekends than on weekdays, and that mode share of fully joint household tours split differently across weekdays and weekends. These studies have provided a general view of joint household activities and modes to access them on weekends using descriptive statistics but no attempts have been made to specify mode choice models for weekend joint household travel. An exception is the study by Hunt et al. (2007) who found in Canada that travel party size and composition are associated with weekend mode choice, signalling joint household travel significantly influences mode choice behaviour. However, their study only introduced travel party size and number of participating persons in different age groups as a simple way to capture household interactions in mode choice and does not consider walking as a mode available for drop-off/pick-up tours nor models joint household travel explicitly.

Within the context of studying travel mode choice and activity patterns, few studies have contrasted the value of travel time savings (VOT) on weekends and weekdays. In the absence of good estimates for weekend VOT, some studies have assumed a lower VOT on weekends than on weekdays due to the more flexible nature of weekend activities (Hunt et al. 2007). The UK and Japan national guidelines for public transport (PT) and road investments, however, suggest a higher VOT on weekends than on weekdays (Prasetyo et al. 2003; Kato et al. 2010; TAG 2011). Prasetyo et al. (2003), using a psychological need approach, provided some explanation to the higher VOT on weekends when people have limited time to participate in joint household activities and physical care that cannot be done on the weekdays.

This brief review indicates that weekend joint household activities and travel warrant more detailed analysis and modelling for a better understanding of differences between weekend and weekday travel behaviour, particularly in the evaluation of policies aimed to ease traffic congestion. This paper extends the literature by investigating weekend joint household activities and mode choices and contrasting this with weekday patterns. The next section describes data sources and the process of constructing the joint tour dataset used in this study.

Data sources and joint tour patterns

The main data source used for this analysis is the Sydney Household Travel Survey (HTS). The Sydney HTS, administered by the Bureau of Transport Statistics (BTS), 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 for each participant and a 24-h travel diary for each participant. The dataset used in this paper is based on pooling data from the 3 years 2007/08, 2008/09 and 2009/10. One specific characteristic of this survey is that all persons in the household participating in the survey are asked to answer a face-to-face interview which increases accuracy. Households that do not have responses from all household members were eliminated from the analysis due to inconsistent travel diaries among household members in terms of joint travel. Within the survey, a question is asked about how many people travel in each car trip and so for car only the travel party size is available. The BTS website gives full details of sampling, method, and data management (BTS 2012).

The HTS data are supplemented by data obtained from the Sydney Strategic Travel Model (STM) on the level of service. This comes from the skim matrices which give estimates of inter-zonal travel times and distances on an average weekday for car mode by four periods of the day (am-peak, inter-peak, pm-peak, and evening) and all PT combined modes in am-peak, for 2,690 travel zones in Sydney. Weekend level of service was estimated from matching weekend traffic volumes and PT timetables to weekday patterns. Technical documentation and standard outputs of the Sydney STM are also available on the BTS website.

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 sequence of trips starting and ending at the individual's home (Shiftan 1998). A small number of tours that started/finished 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 form the longest part of the home-based tour, especially in time (BTS 2011). PT is highest on this adopted hierarchy, followed by car and walking. Another reason for adopting this hierarchy is that walking and car can be considered as feeder modes for PT (Currie and Delbosc 2011). Each trip is a member of a unique home-based tour and is 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.

Intra-household joint tour patterns are identified in two stages. The first stage is to identify joint household trips from unlinked person trip dataset, using flexibly defined matching criteria considering household identifier, reported travel mode, starting and ending times, origin and destination of trips, and the number of household members in the car, adapting Kang and Scott (2011). The number of household members travelling together by other modes is not included in the matching criteria because it is not part of the information available in the Sydney HTS. The reported number of household members in the car is then used to validate the process of identifying joint household trips before chaining unlinked trips into home-based tours. In the second stage, joint home-based tour patterns are identified by connecting and matching relevant trip segments of each household member's tours using a unique home-based tour identifier. This process is executed by an algorithm written in SPSS syntax.

The definitions and descriptions of the nine joint tour patterns, representing nine different ways of arranging household activities and travel into a home-based tour, are provided in Fig. 1 and are adopted from Ho and Mulley (2013). These extend the schema, introduced by Gliebe and Koppelman (2005), whereby separate lines are used to represent the travel paths of each household member relevant to the tours. Different from their methodology, however, this study identifies joint home-based tour patterns for all household members, not just the household heads. Thus, while only two lines (two persons) are used in the patterns of Fig. 1 for illustration purposes, the fully joint tour patterns (J1), for instance, can be extended to match the travel party size. This paper also identifies mixed joint tour patterns (J5–J7) and joint in the middle tours (J8). This is an important extension which helps in differentiating tours based on tour structure and the implied intra-household interactions.

Aggregate characteristics

This section aims to provide a general picture of joint household activities and travel on weekdays and weekends as a precursor to modelling intra-household interactions in travel mode choice. This section first provides a comparative analysis of activity participation and mode of travel across weekdays and weekends before turning to a comparison of weekday and weekend joint household travel.

Activity participation and mode of travel

Figure 2 presents activity participation rates and mode shares by main activity on an average weekday and weekend in Sydney. Percentages are calculated separately for weekday and weekend travel based on the tour's main purpose (column chart) and main mode (bar chart). Figure 2 shows that weekend travel is dominated by maintenance (including shopping, personal business and serving passengers) and discretionary (recreational/social) activities while weekday travel exhibits a more balanced mix of activities: maintenance is the most common (38 %), work is a close second (28 %), followed by discretionary (22 %) and education (12 %). The bar chart in Fig. 2 compares modal shares across weekdays and weekends, segmented by travel purpose. Overall, PT share is much lower on weekends (6 %) than on weekdays (13 %) while the reverse is true for car share. This is partly due to the lower frequency of Sydney public transport service on weekends and partly due to differences in purpose of weekend and weekday travel. Figure 2 demonstrates that it is the activity distribution which is driving the differences in modal share between weekdays and weekends and it is because work and education are the main segments of PT use but weekend travel is mostly non-work, non-education based, PT share is much lower on weekends.

Joint household activity and travel: weekend and weekday patterns

Figure 3 shows the percentage of joint household tour patterns (defined in Fig. 1) by tour main purpose. For all purposes combined, fully joint tour patterns (J1) account for a significant higher share on weekends (46 %) than on weekdays (21 %) with the opposite being true for partially joint tours (J2, J3, and J4). Mixed joint tour patterns (J5, J6, and J7)

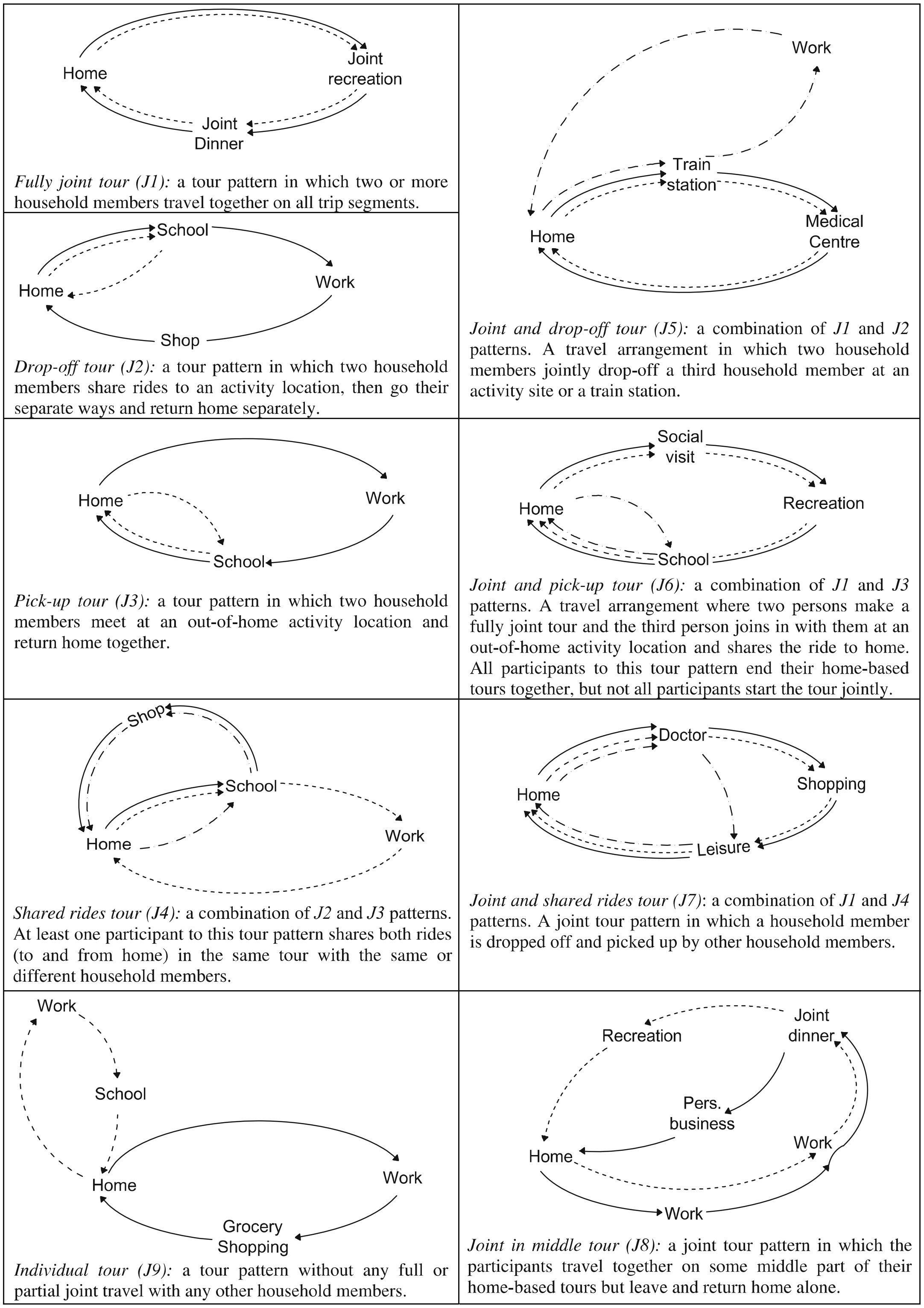

Fig. 1 Typology of joint home-based tours, adopted from Ho and Mulley (2013)

are to a lesser extent more prevalent on weekdays (8 %) than on weekends (5 %). The incidence of joint household tours is highly associated with activity types. Maintenance and discretionary tours are more likely to be undertaken fully jointly by household members while education tours are more likely to be served (i.e., accompanying or

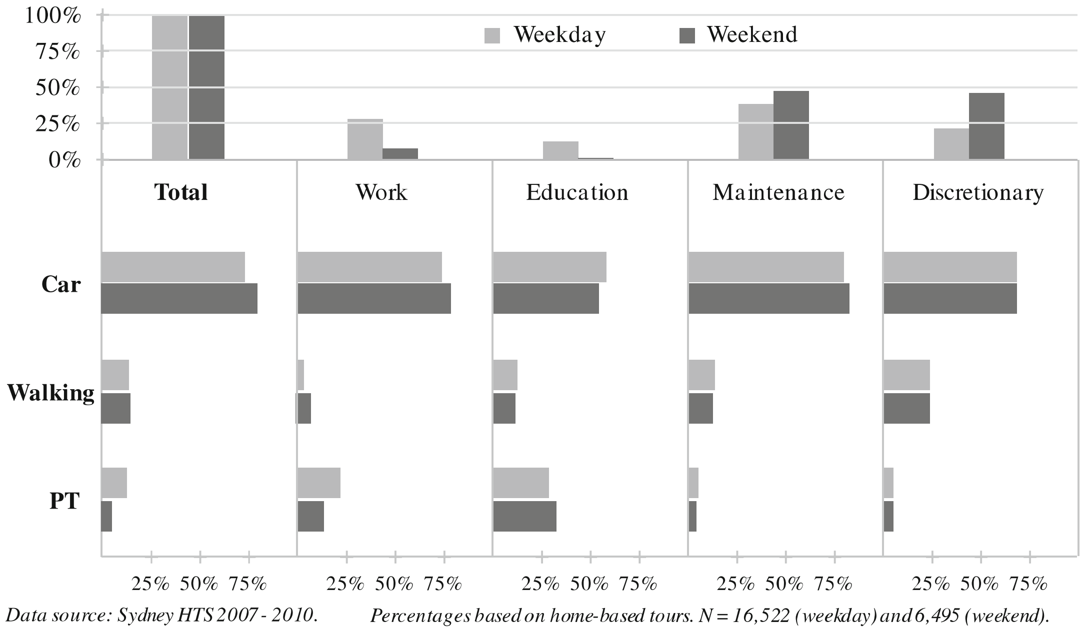

Fig. 2 Distribution of activities and modes of travel: weekday versus weekend

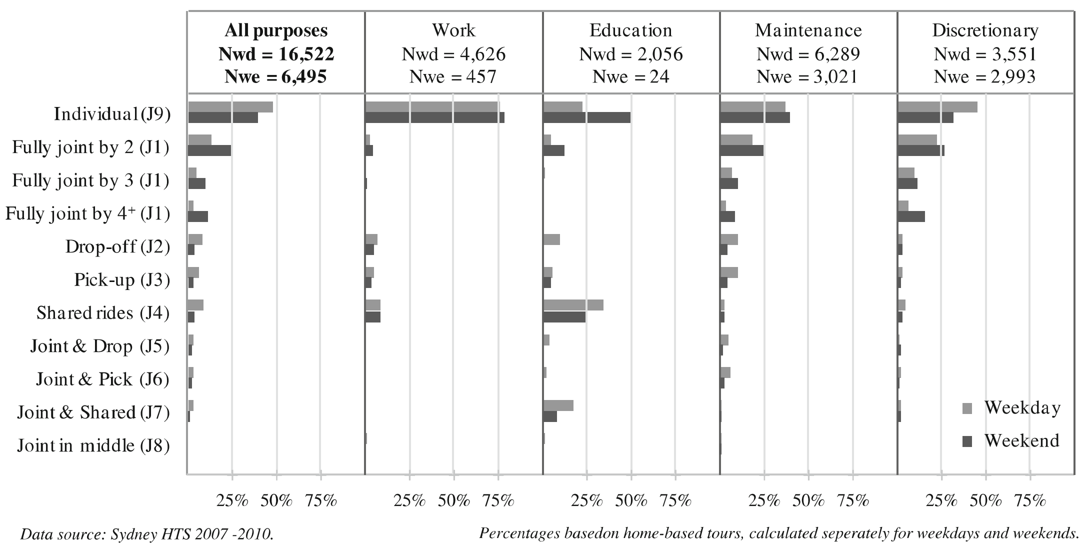

Fig. 3 Distribution of joint household tours, average weekday and weekend in Sydney

providing lift to someone) in both directions, relative to other travel purposes. Holding activity type constant, weekend and weekday joint tour patterns are significantly different, especially for maintenance and discretionary activities using Chi square tests. This suggests that the maintenance and discretionary activities households participate in on weekends are different from those on weekdays. A more detailed investigation of journey purpose for trips chained into maintenance tours reveals that maintenance activities on weekends are directed toward shopping while weekday maintenance activities involve more serving passengers and medical care. For discretionary tours, weekend patterns are more likely to be entertainment and social visits but less recreation than weekday patterns. The prevalence of weekend shopping, entertainment, and social visits lends credence to the argument advanced by Lockwood et al. (2005) that the more relaxed and social nature of weekend activities increases the opportunity for joint household travel arrangement.

The tendency of chaining shared activities into a joint tour pattern is also investigated. Table 1 shows the average occurrence rate and median duration of those shared household activities chained into different joint tour patterns on weekdays and weekends. Fully joint tours (J1) are characterised by a high incidence of shared activities while partially joint tours (J2–J4) are oriented towards individual activities. On average, 67 % of weekday activities chained into a fully joint tour by 2 household members are shared activities, compared to 10 % in the case of a drop-off tour. The incidence of pursuing shared activities on a fully joint tour reduces as the number of people involved in a home-based tour increases. This may be explained by a substantial number of fully joint tours between adults and young children who are not left home alone and taken for the ride when adult household members undertake independent activities.

The propensity to chain shared activities into joint tours is significantly higher on weekends than on weekdays, except for the mixed tours (J5–J7) that are characterised by a very high occurrence of weekday shared activities with short durations. Mixed tour patterns are particularly prevalent in weekday school travel with shared activities being to serve household students to/from school. Shared activities on weekdays are generally shorter than those on weekends. However, the median duration of weekday shared activities chained into the tour type J7 is remarkably long. Further investigation revealed that this pattern is dominated by cases where two students studying at the same school are being dropped off and picked up in the same car tours. This is reinforced by the very short median duration of shared activities chained into the same joint tour on weekends when school activities are not in place.

Travel mode by joint tour pattern

Figure 4 compares weekend with weekday modal shares by joint tour pattern. Differences in mode share between weekend and weekday travel are statistically significant at the 5 % level for all joint tour patterns except for the pick-up (J3) and fully joint tour by 4^+ persons (J1). Car shares increase over the weekend for all joint tour patterns at the expense of PT shares. Also, the walking mode share of J5 and J6 patterns are much higher on weekdays than on weekends. This is unsurprising because these tour patterns are particularly prevalent in weekday school travel (see Fig. 3) which is more likely to be localised and made on foot. Another possible explanation is that the household car is more likely to be available on weekends than on weekdays for joint household activities.

Figure 4 also shows that travel mode shares split differently across joint tour patterns controlling for the effect of weekdays and weekends. The more complex the activity-travel pattern, the more likely the car mode is used with fully joint tours (J1) less likely than partially joint tours (J2, J3, and J4) to involve PT use. This suggests that PT is not as suitable for joint household travel and is more likely to require drop-off/pick-up at either end of the tour.

Modelling mode choice with joint household travel

The aggregate descriptive analysis presented above indicates that weekend activity-travel patterns differ from weekday patterns. This paper therefore models weekend and weekday

Table 1 Shared activities chained into joint tours: occurrence, duration, and difference between weekday and weekend

	Fully joint J1(2)	Fully joint J1(3)	Fully joint J1(4^{+})	Drop off J2	Pick up J3	Shared rides J4	Joint and drop J5	Joint and pick J6	Joint and shared J7
Average occurrence of shared activities (%)									
Weekday	67	44	45	10	17	24	87	89	93
Weekend	80	53	63	16	26	34	90	85	92
Significance level[a]	0.000	0.000	0.000	0.005	0.001	0.000	0.205	0.138	0.517
Median duration of shared activities (min)									
Weekday	75	75	95	10	24	17	13	15	*325*
Weekend	75	88	122	65	58	48	48	50	13
Significance level[b]	0.511	0.064	0.073	0.000	0.039	0.000	0.000	0.006	0.000
Sample size									
Weekday	2,173	777	470	1,277	1,055	1,402	418	458	494
Weekend	1,589	647	734	224	192	222	119	105	96

[a] Differences in average occurrence rates between weekday and weekend are tested with independent samples t test

[b] Differences in median durations of shared activities are tested with the nonparametric median test

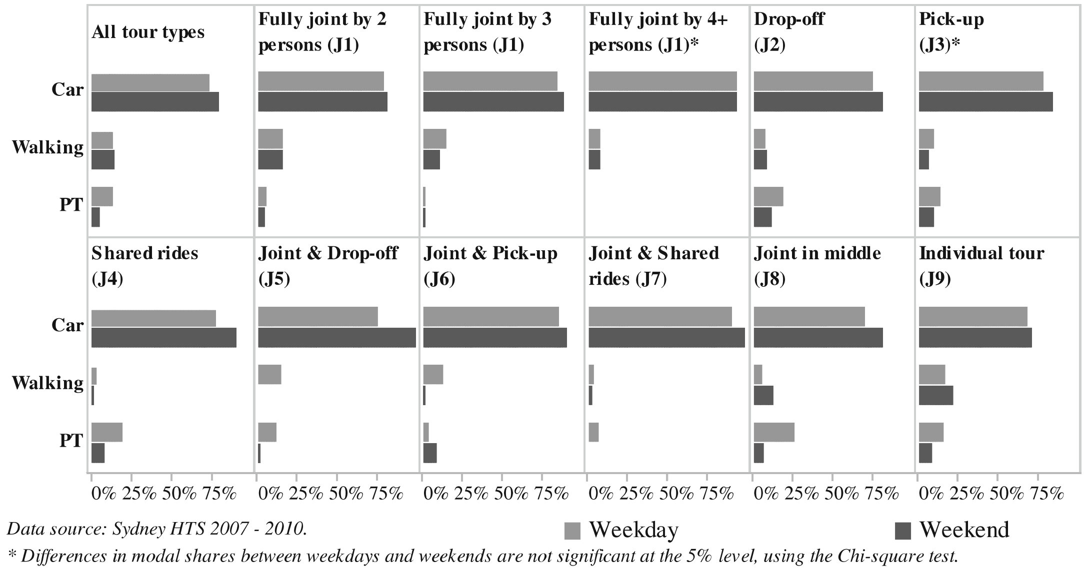

Fig. 4 Tour-based mode share by joint tour pattern, weekend versus weekday in Sydney

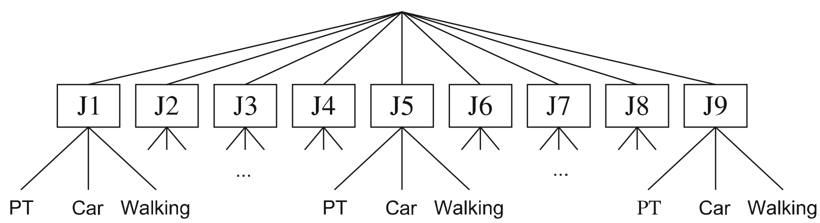

Fig. 5 Tree structure for mode choice model with joint household travel

travel patterns separately. The weekend and weekday models, however, share the common model structure discussed in the next sub-section.

Model structure

The individual choices of joint travel patterns and travel modes are modelled simultaneously at the tour level by a nested logit model shown in Fig. 5. At the tour level, the main travel purposes of all tours undertaken by each household member are known and can be used as explanatory variables. It is assumed that the main destination and time of day (departure and arrival times) is known for each tour. As is common in the activity based modelling literature, the assumptions made here include that activity generation and location precede mode choice and that the choice of the time of day travel for the main activity is known prior to the travel mode decision (Bradley and Bowman 2006; Davidson et al. 2007; Ye et al. 2007). In this approach, there is no constraints on individual choices to ensure consistency between the individuals of the same household but in the upper level household members are assumed to match their activity agendas to identify the needs for and the possibilities of travelling together for the entire tour or for some trip segments of the tour. This upper level is in some way analogous to the escorting model recently developed and incorporated in the CT-RAMP family of activity-based models (Vovsha and Petersen 2005; Davidson et al. 2011). However, the model shown in Fig. 5 is applicable for all joint travel purposes and not just escorting children to school. In the model, each household member is assumed to choose the main travel mode to maximise their personal utility, conditional on their choice of joint travel patterns.

The lower level represents individual's choice of main travel mode between PT, car and walking. Compared to the escorting model mentioned above, this model explicitly considers the possibility of escorting and ridesharing by all travel modes and not just the car mode. The observed choice of travel mode for each joint tour pattern is the dependent variable and the individual is the decision-making unit in this model. Thus, this is not a group model *per se*, but rather an individual decision model with joint household travel arrangements being explicitly incorporated through the typology of joint household tours that embed the household members' agreement upon time and space constraints for the journey.

The choice structure considers all possible combinations of joint tour arrangements and travel modes. Not all joint tour patterns are available to each household. Single-person households, for instance, only have three alternatives corresponding to the individual tour pattern (J9) in their choice set while households with 4^{+} persons have all identified alternatives in their choice set. It should be noted that joint tour patterns are further split or combined slightly differently in the weekday and the weekend models due to different rates of occurrence of joint tour patterns on weekdays and weekends (see Fig. 4 and the model summary statistics below).

The model specification examines the effects of tour attributes, transport-related fringe benefits alongside household, individual characteristics and their interactions. Joint household travel arrangements are assumed to be motivated by social and mobility constraints (e.g., young children do not normally travel alone), household context (e.g., larger households have a higher opportunity to coordinate joint household travel), and situational factors such as travel purposes. Thus, the utility function is specified at the upper level to capture motivation and constraints. The propensity to arrange joint household activities and shared rides into home-based tours is also influenced by the household resources such as time and mobility-unrestricted persons, the availability of travel modes and their associated level of services. This is reflected through logsums entered into the upper level from the individual mode choice level below.

Model summary statistics

Table 2 presents summary statistics and inclusive value (IV) parameters for both weekend and weekday models. The weekend model has 24 alternatives grouping into 8 nests, based on joint tour patterns. The joint in middle tour pattern (J8) was combined with the individual tour pattern (J9) while all mixed joint tour patterns (J5, J6, J7) were treated as one group in the weekend model due to their similarity and rarity on weekends. Conversely, the fully joint tour pattern (J1) was further split according to the travel party size with four household members being the maximum in the weekend model, as opposed to three household members in the weekday model (discussed further in Ho and Mulley 2013).

As indicated by Mc-Fadden R-squared, both models fit reasonably well to the data. Setting one IV parameter in each model to one, IV parameters of the other nests are well estimated. The IV parameters lie significantly between zero and one, indicating that this partition is consistent with random utility theory. As alternatives within the same nest are more likely to be substituted for each other than for alternatives in different nests, the estimation results indicate that decision-makers are more likely to substitute travel modes between car, PT and walking to undertake the same joint household travel pattern, as opposed to changing their travel pattern due to the unavailability of a travel mode. From

Table 2 Summary statistics of weekend and weekday tour-based mode choice models

Summary statistics	Weekend	Weekday
Number of observations	6,495	16,522
Number of alternatives	24	30
Number of parameters	77	92
Log likelihood at convergence	−10,626	−30,169
Log likelihood at market shares	−12,015	−35,896
Log likelihood at zeros	−20,641	−56,195
Mc-Fadden R-squared (vs. zeros)	0.485	0.463
Mc-Fadden R-squared (vs. constants)	0.116	0.159
Inclusive value parameters[a]		
Individual tour (J9)	*1.0 (fixed)*	0.758 (5.71)
Joint in middle tour (J8)	*1.0 (fixed)*	0.461 (4.77)
Fully joint tour by 2 persons (J1)	0.830 (2.32)	0.710 (4.23)
Fully joint tour by 3 persons (J1)	0.519 (5.44)	0.534 (7.15)
Fully joint tour by 4^+ persons (J1)	0.590 (3.10)	n/a
Drop-off tour (J2)	0.790 (2.32)	0.503 (10.8)
Pick-up tour (J3)	0.559 (3.42)	0.489 (10.6)
Shared rides tour (J4)	0.257 (12.5)	0.314 (27.2)
Joint and drop-off tour (J5)	*0.301 (6.64)*	0.447 (8.14)
Joint and pick-up tour (J6)	*0.301 (6.64)*	1.0 (fixed)
Joint and shared rides tour (J7)	*0.301 (6.64)*	0.493 (4.04)

Italicized values in the weekend column indicate joint tour patterns combined for modelling

n/a not applicable in the weekday model

[a] t-values versus 1.0 are in parentheses

the activity-based travel behaviour point of view, where travel is considered as a derived demand, these results are consistent with expectations.

Weekend joint household activities and travel

Parameter estimates for variables affecting the arrangement of joint household activities and travel on weekends and weekdays are presented in Table 3. The weekday model results are presented but are presented for comparison only with discussion available in Ho and Mulley (2013).

Table 3 shows that all estimated parameters have the expected sign and plausible magnitudes. Considering the separate joint tour patterns, it can be seen that the incidence of particular joint tour patterns are strongly associated with person type, with children being more likely to accompany adults who give lifts to other household members (indicated by positive estimates for mixed tour patterns J5–J7). As children get older, the need for adult accompaniment and chauffeuring decreases. This is reflected through a decrease in magnitude of parameters associated with children age variables in the utility function of individual (J9, J8) and fully joint tour (J1) by three persons patterns in the weekend model. The weekday model results offer similar observations but on the shared rides pattern (J4) as opposed to fully joint tour patterns (J1). This would appear logical as serving children tours are directed toward education activities on weekdays while they are leisure-oriented

Table 3 Formation of joint household activities and shared rides, Sydney 2007–2010

Variable	Individual J9, J8	Fully joint J1(2)	Fully joint J1(3)	Fully joint J1(4^+)	Drop off J2	Pick up J3	Shared rides J4	Mixed tour J5–J7
(a) Weekend								
Children aged up to 5	−2.390		0.977					0.530
Children aged 6–10	−1.715		0.413				0.780	0.530
Children aged 11–15								0.530
Maintenance tour	−0.778	1.788	3.087	3.855			−0.539	
Discretionary tour	−0.753	2.070	3.465	4.584		−0.510		
Mother of mix aged children (aged 0–5 and 6–16)			1.484	1.167				
Household w/5^+ persons		−0.372		0.252	0.698	0.698		0.914
Constant	1.345	−0.144[b]	−1.700	−1.690[a]		0.098[b]	0.387	0.547

Variable	Individual J9	Fully joint J1(2)	Fully joint J1(3^+)	Drop off J2	Pick up J3	Shared rides J4	Joint and drop J5	Joint and pick J6	Joint and shared J7
(b) Weekday									
Children aged up to 5	−3.460					0.700	1.527	1.527	1.300
Children aged 6–10	−2.979					0.614			1.891
Children aged 11–15	−1.355					0.441			
Education tour	−0.628			0.326					
Maintenance tour		2.649	3.600	1.288	1.443				
Discretionary tour		2.720	4.050						
Mother of mix aged children (aged 0–5 and 6–16)			0.669				2.680	2.680	
Household w/5^+ persons			0.187				0.700	0.700	0.700
Constant	4.412	0.946	−.090[b]	1.179	0.857	2.602	0.848	0.911	0.781

All parameters are significant at the 5 % level or less unless otherwise indicated

[a] Not significant at the 5 % level

[b] Not significant at the 10 % level

on weekends (as discussed above in section "Joint household activity and travel: weekend and weekday patterns"). Vovsha and Petersen (2005) report similar results with older students being more likely to travel independently to school.

Maintenance and discretionary activities on the weekend are statistically significantly more likely to be joint with other household members than work (base) and education activities. Also, the term 'the more the merrier' is clearly reflected in these coefficients. Gender differences in household activities allocation are evident with mothers being the primary care givers for children over the weekend even though fathers are more likely to be not working. Compared to weekday patterns, the mothers' responsibilities on weekends involve more accompanying and less chauffeuring.

Drop-off and pick-up arrangements appear to be unpopular choices on weekends with only large households (with five or more people) showing a higher propensity to take joint tour patterns J2, J3, and J5–J7. This is not unexpected given the more flexible nature of weekend activities and the higher opportunity to coordinate joint travel in the form of drop-offs and pick-ups for members of large households.

Weekend mode choice

Parameter estimates for variables affecting individuals' mode choices for all joint tour patterns are presented in Table 4a (weekend) and Table 4b (weekday) for comparison purposes. At the individual mode choice level, car is the reference for each of the joint tour patterns with no alternative-specific constants being specified for car alternatives. As in case of the individual choice of joint tour patterns discussed above, all parameters have the expected signs. The level of service variables (travel times and cost) were well estimated and did not need to be constrained. VOT can be computed from these parameters and are discussed in the next section. Other variables significantly affecting tour-based mode choices on weekends include household characteristics, individual characteristics, and transport-related fringe benefits.

There are a number of strong messages from Table 4a. Mode choice over the weekend is strongly linked to household car ownership and income with high levels of household income and car ownership being associated with less PT use and walking. No-car households, who are PT captive users, show a higher propensity to use PT even for fully joint household activities, although the travel party of three or more household members decreases this propensity. Car-negotiating households (i.e., households with fewer cars than drivers) walk significantly more than car-sufficient households for joint activities on weekends. In addition, students over 15 years old remain the main PT users on weekends with or without intra-household drop-offs/pick-ups. They are less likely to involve in joint household activities with four or more household members. Importantly, of the different transport-related fringe benefits that can be provided to the employee, the provision of fuel costs remains a significant barrier to PT use on weekends as with weekdays. Conversely, although the provision of PT fares significantly increases PT on weekday travel, it appears to have an insignificant effect on weekend travel.

Values of travel time: weekend vs. weekday

The values of travel time savings (VOT) on weekends and weekdays, calculated from the parameter estimates associated with travel times and travel costs in each model, are shown in Table 5. In-vehicle time, wait time, and walk time are valued respectively at \$6.81, \$11.28, and \$14.68 per person hour for weekday travel in 2008 Australian dollars. These

Table 4 Estimation results for mode choice of all joint tour patterns, Sydney 2007–2010

Variable	Individual J9, J8	Fully Joint J1(2)	Fully Joint J1(3)	Fully Joint J1 (4^{+})	Drop off J2	Pick up J3	Shared rides J4	Mixed tour J5–J7
(a) Weekend								
All modes								
Travel cost (AU$)	−0.081	−0.081	−0.081	−0.081	−0.081	−0.081	−0.081	−0.081
In-vehicle time (min)	−0.012	−0.012	−0.012	−0.012	−0.012	−0.012	−0.012	−0.012
Wait time (min)	−0.021	−0.021	−0.021	−0.021	−0.021	−0.021	−0.021	−0.021
Walk time (min)	−0.032	−0.032	−0.032	−0.032	−0.032	−0.032	−0.032	−0.032
Public transport								
Fuel cost provided	−1.343							
No-car household	2.002	1.922						
HH income > AU$67.6 k		−0.453[a]						
Student over 15 years old	0.810					0.668	0.351[a]	
Constant	0.077[b]	−1.050	−1.286	−2.268	−0.549	−0.448[a]	−0.098[b]	−0.241[b]
Walking								
No-car household	2.022	1.823	2.049					
Car-negotiating household		0.773	0.778					
HH income > AU$67.6 k				−0.559				
Constant	2.679	0.839	0.233[b]	0.501	0.348[b]	0.351[b]	0.135[b]	0.029[b]
Car								
No-car household				0.759				
HH income > AU$67.6 k				−0.341				
Student over 15 years old				−0.776				
Retiree	−0.190			−1.078				
Licence holder	1.973	0.649						

Table 4 continued

Variable	Individual J9	Fully joint J1(2)	Fully joint J1(3^+)	Drop off J2	Pick up J3	Shared rides J4	Joint and drop J5	Joint and pick J6	Joint and shared J7	Joint in middle J8
(b) Weekday										
Travel cost (2008 AU$), generic	−0.091	−0.091	−0.091	−0.091	−0.091	−0.091	−0.091	−0.091	−0.091	−0.091
In-vehicle-time (min), generic	−0.010	−0.010	−0.010	−0.010	−0.010	−0.010	−0.010	−0.010	−0.010	−0.010
Walk time (min), generic	−0.022	−0.022	−0.022	−0.022	−0.022	−0.022	−0.022	−0.022	−0.022	−0.022
Wait time (min), 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	1.337	1.222								
Car-negotiating household				0.111[a]	0.111[a]					
Household income > AU$67,600		−0.443		0.279		0.112[a]				
Tour involved children				−0.421	−0.377					
Student over 15 years old	0.309				0.555	0.379				
Retiree				−0.610						
Flexible working hours	0.621			0.621						
PT fare provided	0.645									
Free parking provided	−0.748			−0.465						
Fuel cost provided	−1.888									
Constant	−0.427	−0.912	−1.658	0.663	0.630	−0.283	−0.350	−2.474	−0.897	0.117[b]
Walking										
No-car household	1.243			0.618	0.618	0.618				
Car-negotiating household							0.422	0.422	0.422	
Household income > AU$67,600					−0.327	−0.179[a]				
Retiree	0.142									

Table 4 continued

Variable	Individual J9	Fully joint J1(2)	Fully joint J1(3^+)	Drop off J2	Pick up J3	Shared rides J4	Joint and drop J5	Joint and pick J6	Joint and shared J7	Joint in middle J8
Constant	0.834	0.629	0.211	0.813	1.242	0.039[b]	0.329	−0.239[b]	−0.643	0.162[b]
Car										
Student over 15 years old		−0.290	−0.290							
Licence holder		0.342		1.081	1.197	−0.459			−0.704	

All parameters are significant at the 5 % level or less unless otherwise indicated

HH household

[a] Not significant at the 5 % level

[b] Not significant at the 10 % level

absolute values are in line with empirical evidence of VOTs in Australia as well as its official recommendations (ATC 2006; Hensher et al. 2011; Litman 2011). Although it is difficult to compare directly the VOT across studies due to different price bases and market segments, this model delivers the average VOT that belongs to a "behaviourally 'appealing' range of willingness to pay: $6.30 per person hour to $9.65 per person hour" (Hensher et al. 2011, p. 968). The implied relative in-vehicle time values to wait and walk time on weekdays are 1.66 (11.28/6.81) and 2.16 (14.68/6.81), which are also consistent with international evidence (Kato et al. 2010; Abrantes and Wardman 2011 among many others). This evidence lends support for the modelling approach adopted in this paper which assumes activity generation and joint travel arrangement precede mode choice.

Comparing this with the weekend model shows the average VOTs are higher on weekends than on weekdays. Although Australian VOTs on weekends are not available to compare with the model results, the results are in line with official guidelines currently used in other developed nations (UK, Japan, Norway) and empirical evidence found elsewhere (Ramjerdi et al. 1997; Prasetyo et al. 2003; Kato et al. 2010; TAG 2011).

Policy analysis

The estimated models are used in this section to simulate the modal shifts that result from changes to transport policy and the level of services. The procedure for estimating modal shift for each scenario includes a three-step process:

(1) The estimated parameters and the estimation sample data are used to compute the base mode shares.
(2) The influence of changes to policy or level of services is simulated by changing a specific variable in the estimation data of the affected alternatives before applying the model to identify new estimated mode shares.
(3) The estimated modal shift is calculated using the results from steps 1 and 2.

Table 6 compares the modal shift on a weekday with that for a weekend day in response to the scenarios of a 20 % reduction in PT fare, a change in travel time, and the

Table 5 Values of time per person hour (AU$ 2008)

Time component	Weekday	Weekend
In-vehicle time	$6.81	$8.74
Wait time	$11.28	$15.26
Walk time	$14.68	$23.59

Table 6 Estimation of modal shifts in response to same scenarios on weekday and weekend

Modal	−20 % PT fare		Change in travel time		PT fare deal[a]	
Shift	Weekday (%)	Weekend (%)	Weekday (%)	Weekend (%)	Weekday (%)	Weekend (%)
Car	−1.0	−0.3	−1.8	−0.5	−0.3	−0.4
PT	1.1	0.4	1.8	0.5	0.3	0.4
Walking	−0.1	−0.1	0.0	0.0	0.0	0.0

[a] Applied to group travel only

introduction of a PT fare 'deal' aiming at group travel. The impact of a change in travel time corresponds to a policy of implementing high occupancy vehicle (HOV) lanes and is simulated in this analysis by reducing in-vehicle time by 20 % for car tours involving joint travel and all PT tours while increasing 20 % of in-vehicle travel time for other car tours. The aim of this simulation is not to provide a reasonable prediction of modal shift due to the introduction of HOV lanes per se but to understand the differences between weekday and weekend responses for joint travel in this case. The 'fare deal' scenario is simulated by adjusting PT costs for group travel a maximum of $2.50 per person, using the ticket price that currently applies to Family Funday Sunday ticket in Sydney (NSW 2012).

With a simple reduction of PT fares, a higher modal shift from car to PT is predicted for weekdays as compared to weekends. This is expected as weekend travel is characterised by a higher proportion of joint household travel with people preferring to travel by car as this is cheaper per person than using PT even with a fare reduction. Weekday travel involves a higher proportion of individual tours than weekend travel and this explains the higher modal shift on weekdays than on weekends for the scenario simulating the introduction of HOV lanes (i.e., because there are more individual travel on weekdays, the target population affected by these policy changes has a proportionately bigger impact). Similarly, PT fare deals aiming at group travel appear to be more successful on weekends than on weekdays because again the targeted market is larger on weekends. Compared to the simple fare increase and the impact of reducing travel time for joint travel using say, HOV/HOT lanes above, the difference between weekday and weekend responses to a PT group fare deal is quantitatively smaller but this might be expected from the lower frequency of Sydney PT services on weekends and from the way in which a high proportion of weekend joint travel involves three or more household members when it could be cheaper to use a household car.

Conclusions and discussion

This paper has examined the joint household travel arrangements and mode choices for weekends and has contrasted these with weekday patterns. The paper offers an analytical approach to modelling an individual's tour-based mode choice where a variety of patterns of joint household activities and shared ride arrangements are incorporated explicitly within a clear theoretical framework of random utility maximisation.

The model contributes to the growing literature on modelling intra-household interactions, an essential element in advanced activity-based models, in a number of ways. First, the model considers joint activity-travel patterns amongst all household members, not just between household heads or between parents and children. Second, various patterns of intra-household interactions in daily travel under social, temporal and spatial constraints are effectively captured by the typology of joint household tour patterns embedded in the model, avoiding the unnecessary assumptions of previous approaches such as serve household passengers travel is made by car only and is allocated directly to the passenger's activity. Finally, by modelling individual choice of joint tour patterns and mode choice at the tour level, this paper adds an additional 'layer of interactions' to the activity-based modelling framework in which household interactions have extensively been modelled at three layers of daily activity patterns (DAP), joint activity participation, and allocation of maintenance activities among household members (Vovsha et al. 2003, 2004; Bhat and Pendyala 2005; Bradley and Vovsha 2005; Gliebe and Koppelman 2005).

By separating weekend activity-travel from their weekday counterparts, this paper is able to quantify empirically differences using data from 3 years pooled Sydney Household Travel Survey. Weekend and weekday activity-travel patterns are compared along several dimensions with a specific focus on joint household activities and shared ride arrangements. The results show that more than 90 % of weekend travel is directed toward maintenance and recreational/social activities and is characterised by a higher joint household activity participation rate. In contrast, weekday travel is more oriented to work and education-related activities and is distinguished by more intra-household shared ride arrangements. These differences in household activities and travel patterns over weekends and weekdays are associated with different mode shares and hence require different transport management measures aimed to alleviate traffic congestion on weekdays and weekends. For instance, *ceteris paribus*, the same reduction of PT fares has found through the scenario analysis to result in a lower modal shift from car to PT on weekends than on weekdays. Joint household travel is likely to be cheaper per person (averaged over all occupants) by car than PT and, as joint travel accounts for a much larger proportion of travel on a weekend than on a weekday, there is a lower potential market for modal shift on a weekend than on a weekday.

Joint household travel, either fully or partially, accounts for about 60 % of all home-based tours on weekends and about 50 % on weekdays. This emphasises the importance of analysing and modelling intra-household interactions explicitly for improved travel demand forecasting and policy analysis. The results of this paper indicate that household resources (e.g., car availability, mobility-unrestricted persons), mobility and social constraints, and opportunities to coordinate household members' activities and travel play an important role in arranging joint household travel. Specifically, the age of the individual, travel purpose, and household structure are the three most important determinants of whether out-of-home activities are accessed jointly or individually. In addition, the VOT on weekends is found to be higher than that on weekdays. These additional pieces of information are useful for policy-making related to, for example, the introduction of HOV/toll lanes or PT group fare 'deals' with the former being shown to be more successful on weekdays and the latter on weekends.

Improvements to modelling may be achieved in many directions. One potential enhancement is by taking account individual preference heterogeneity and the state dependence of joint household travel and mode choices of multiple tours undertaken by each person. This represents an important direction for further research as young children, for instance, who are more likely to be chauffeured to school, are also more likely to be served when participating in non-education activities. Also, as evidenced by the analysis of shared activities chained into joint tours, households with more than one student attending the same school are very likely to drop-off/pick-up students using the same car tour. This is unsurprising but implies that escorting models should consider the possibility of serving multiple school students concurrently as opposed to the current practice of modelling these sequentially. Another important step will be to collect and integrate land use data and time synchronisation variables into the mode choice model developed in this paper for a more rigorous analysis of household interactions under household resource, social, temporal, and spatial setting.

More generally, the current modelling technique treats the individual as the decision-making unit and uses a typology of joint household tours as a means to incorporate intra-household interactions. For some joint household travel arrangements, a group decision model that allows different household members to play different roles such as the PCCL model developed by Gliebe and Koppelman (2005) may add more insights into joint household travel arrangements. This requires further methodological developments to capture complex interdependent decisions of multiple-person households.

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