AN INVESTIGATION OF INTRA-HOUSEHOLD INTERACTIONS IN TRAVEL MODE CHOICE

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A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

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2013
Abstract

The individual has traditionally been treated as the decision-making unit, even if the individual behaviour is contingent on interaction between household members. Intra-household interactions can be observed not only in daily travel-activity patterns such as activity participation and the allocation of household resources and tasks, but also in long-term decisions of residential location choice and vehicle ownership. Within the context of modelling short-term activity travel demand, this study aims to investigate the influence of intra-household interaction and provide a micro-approach to the effect of land use factors on travel mode choice. The current research overcomes several limitations in the literature. First, intra-household interaction is treated as context-dependent in the sense that it depends on household characteristics, environmental setting, and choice situation. Second, the modelling approach considers joint activity-travel patterns amongst all household members, not just between household heads or between parents and children. Third, land use characteristics are measured at the micro-level, providing more rigorous evidence to support transport policy and planning practices. Fourth, this study analyses joint activity-travel patterns for both weekdays and weekends in contrast to the existing literature which has focused extensively on weekday behaviour. Finally, this research deals with travel mode choice which is an important research focus for operational travel demand models yet remains largely unexplored in the literature looking at intra-household interactions.

This thesis develops a modelling framework to integrate intra-household interactions with tour-based mode choice, using the three years pooled Sydney Household Travel Survey data. The empirical analysis is based on a nested logit model which formulates the individual choice of travel mode 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. The findings provide evidence of intra-household interactions in travel mode choice of each household member and highlight factors associated with joint household activities and shared ride arrangements, with a distinction between weekdays and weekends. The results indicate that household resources, mobility and social constraints, and opportunities to coordinate household members’ activities play an important role in arranging joint household travel. Also, modelling outputs signal the differences that interpersonal interactions make to model elasticities and the implications for transport policy.

The originality and the contribution of this research lie in four main areas. First, it tests the relevance of interactions between household members to household mode choice decisions
and adds an additional ‘layer of interactions’ to the activity-based modelling framework. The study offers an analysis of household travel decisions embedding context and situation effects, thereby reflecting more realistically the nature of travel decisions. Second, this study offers a typology of joint household tour patterns embedded in a modelling approach which permits a variety of activity-travel patterns amongst all household members together with intra-household interactions. Third, the research provides evidence on the effects of land use factors measured at the micro-level so as to identify which aspects of the built environment are most likely to support policy change for sustainable transport choices. Finally, by separating weekend activity-travel from their weekday counterparts, this study is able to quantify empirically differences which suggest different transport management measures aimed to alleviate traffic congestion and promote public transport use.
Statement of Originality

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes. I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Chinh Q. Ho
ACKNOWLEDGEMENTS

My first acknowledgments are to my supervisors, Professors Corinne Mulley, Michael Bell, and Dr. Rhonda Daniels. Corinne made me feel the Institute of Transport and Logistics Studies at the University of Sydney is the best place for me to pursue my doctoral study, from the very first day of this journey when I approached her to ask if she is willing to supervise my research. In the progression of my candidature, Corinne has played many different roles including supervisor, mentor, co-author, and boss. In each of these roles, she has guided me to develop my research ability, cope with stresses and challenges of the study, and build up my research network. I am deeply grateful to Corinne for her tremendous support, great encouragement, insightful comments and the opportunities given over the course of my doctoral study. I also highly appreciate valuable feedback and information from Michael, who is my associate supervisor in the final stage of this study after my former supervisor, Dr. Rhonda Daniels, left the Institute. Rhonda’s practical experience and local knowledge in transport planning, policy and data have undoubtedly helped me to lay the foundation of this work and build up my ability to see issues from a practical viewpoint. At her suggestion, I have gained much spatial knowledge on Sydney land use patterns and transport planning from many Sunday outings to different suburbs in my early days of Sydney resident.

It is a friendly and interactive environment at ITLS that makes it an excellent place to work, and for which I truly appreciate the people who create and maintain it. Professor David Hensher’s passion, experience, ability alongside his valuable comments keep motivating me to think of the big picture while digging deep into the issues. Professor John Rose’s classes in discrete choice models and experimental designs strengthened my understanding of various models and showed me alternative directions for intellectual inquiry, while his detailed comments on my work were equally important. I am also thankful to Professors Peter Stopher and Michiel Bliemer for their valuable comments and insistence on clarity when writing and presenting. It has also been my great pleasure to work with fellow doctoral candidates in the Institute, especially Patrick, Alejandro, Adrian, Richard, Asif and Waiyan who have given their support on both research and personal matters.

I have no doubt that this work would not have been possible without the contribution of the Bureau of Transport Statistics (BTS), Transport for New South Wales. I am indebted to the patient mentoring and friendship of the client service team in BTS. In particular, the support of Evelyn Karantonis, Annette Hay, Yun Zhang, Charlie Lin, and Frank Milthorpe is greatly
appreciated. In addition, the most supportive staff that I could imagine, Kerry Shaz, deserves special thanks not only for processing my data request very quickly but also for recommending me to BTS, where I am proud to be an employee even for only a short term of six months. My acknowledgements are extended to Michael Tanner, Houshang Farabi, and Thangarajah Praba who have helped me with extracting land use data and making GIS layers available for use in this thesis.

Last but not least, I would like to thank my family and family-in-law for giving immense support and encouragement, and guiding me towards the real value of life. They had to endure my whingeing when things were not going well and taught me the importance of keeping an optimistic view. I thank my long-suffering wife Minh, who sacrificed her job to come and support my study and spent far too much time on housework, so that I could accomplish this thesis and soon can make our life more colourful with weekends away, travelling and going fishing as I promised. This thesis is dedicated to my brother Cuong, who does not get much chance to go to school due to his physical condition.

This work was funded by the University of Sydney International Scholarship (USydIS).
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<th>Description</th>
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<tbody>
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<td>ABS</td>
<td>Australian Bureau of Statistics.</td>
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<tr>
<td>ACT</td>
<td>Australian Capital Territory.</td>
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<td>BTS</td>
<td>Bureau of Transport Statistics.</td>
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<tr>
<td>CBD</td>
<td>Central Business District.</td>
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<td>DAP</td>
<td>Daily Activity Pattern.</td>
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<td>HATS</td>
<td>Household Activity Travel Simulator.</td>
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<td>HII</td>
<td>Hierarchical Information Integration.</td>
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<td>HTS</td>
<td>Household Travel Survey.</td>
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<td>HOT lanes</td>
<td>High Occupancy Toll lanes.</td>
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<td>HOV</td>
<td>High Occupancy Vehicle.</td>
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<td>IACEs</td>
<td>Interactive Agency Choice Experiments.</td>
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<td>ID</td>
<td>Identifier.</td>
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<tr>
<td>IIA</td>
<td>Independent of Irrelevant Alternatives.</td>
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<tr>
<td>IID</td>
<td>Independently and Identically Distributed.</td>
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<tr>
<td>IPART</td>
<td>Independent Pricing and Regulatory Tribunal.</td>
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<td>IV</td>
<td>Inclusive Value.</td>
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<td>K&amp;R</td>
<td>Kiss and Ride.</td>
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<td>GEV</td>
<td>Generalised Extreme Value models.</td>
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<tr>
<td>GIS</td>
<td>Geographical Information System.</td>
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<td>GMA</td>
<td>Greater Metropolitan Area.</td>
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<td>gPCCL</td>
<td>Generalised Parallel Choice Constrained Logit model.</td>
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<td>LC</td>
<td>Latent Class model.</td>
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<td>LGA</td>
<td>Local Government Area.</td>
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<td>MBCR</td>
<td>Metropolitan Bus Contract Region.</td>
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<td>MNL</td>
<td>Multinomial Logit model.</td>
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<td>MPMD</td>
<td>Multiple Purposes at Multiple Destinations.</td>
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<tr>
<td>MPSD</td>
<td>Multiple Purposes at Single Destination.</td>
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<td>NL</td>
<td>Nested Logit model.</td>
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<td>NSW</td>
<td>New South Wales.</td>
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<tr>
<td>OMBCR</td>
<td>Outer Metropolitan Bus Contract Region.</td>
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<td>PCCL</td>
<td>Parallel Choice Constrained Logit model.</td>
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<td>PT</td>
<td>Public Transport.</td>
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<td>PWSE</td>
<td>Probability Weighted Sample Enumeration</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>P&amp;R</td>
<td>Park and Ride.</td>
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<td>SD</td>
<td>Statistical Division.</td>
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<tr>
<td>SUR</td>
<td>Seemingly Unrelated Regression model.</td>
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<td>SEM</td>
<td>Structural Equations Model.</td>
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<td>SP</td>
<td>Stated Preference.</td>
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<tr>
<td>SPSD</td>
<td>Single Purpose at Single Destination.</td>
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<tr>
<td>STA</td>
<td>State Transit Authority</td>
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<tr>
<td>STM</td>
<td>Strategic Travel Model.</td>
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<td>SSD</td>
<td>Sub-Statistical Division.</td>
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<td>TZ</td>
<td>Travel Zone.</td>
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<tr>
<td>RP</td>
<td>Revealed Preference.</td>
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<td>VOT</td>
<td>Value of Time</td>
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Glossary

Note: Cross reference within the glossary is indicated by italic text.

Am-peak
Peak hours in the morning on a weekday are between 7 and 9 am, unless otherwise indicated.

Average weekday
Average of travel over all Mondays to Fridays.

Average weekend
Average of travel over all Saturdays and Sundays.

Active modes
Walking and cycling.

Car-negotiating household
A household with fewer cars than car driving licence holders (i.e. drivers)

Car-sufficient household
A household with as many cars as car driving licence holders (i.e. drivers)

Daily Activity Pattern (DAP)
A sequence of tours undertaken in a day by an individual.

Extended am-peak
Am-peak extended on a weekday to between 6 and 10 am.

Home-based tour
A sequence of trips that start and end at the individual’s home.

Household trip
A trip made by one or more individuals in the same household. A household trip can be solo or joint. A household trip made jointly by two household members equals to two person trips.

Individual tour
A home-based tour without any trip segment made jointly with one or more household members. Joint travel only with non-household members is still considered as individual travel.

Inter-peak
Time period between the am-peak and the pm-peak on a weekday, between 9 am and 3 pm where not extended.
**Intervening activity**
An activity other than changing mode and returning home.

**Inter-zonal travel**
Travel across more than one *travel zone* boundary.

**Intra-zonal travel**
Travel entirely within a *travel zone* boundary.

**Joint tour**
A home-based tour that contains one or more trip segments made jointly with one or more household members.

**Joint trip**
A trip which is made jointly with one or more household members.

**Linked trip**
A journey from one activity to another comprising of one or more unlinked trips.

**Pm-peak**
Peak hours in the afternoon on a weekday are between 3 and 6 pm, unless otherwise indicated.

**Public transport (PT)**
Ferry, train, light rail, bus, and taxi.

**Person trip**
A trip made by a person. A *joint trip* by two persons equals to two person trips.

**Solo trip**
A trip which is made individually (i.e. without joint travel with any other household member).

**Travel zone (TZ)**
A geographic area used for travel modelling. The study area is divided into TZs without overlap or omission.

**Tour main mode**
The main travel mode of the entire tour, assigned on a hierarchical basis.

**Tour main purpose**
The main travel purpose of the entire tour, assigned on a hierarchical basis.

**Travel zone centroid**
The geographic centre of a travel zone.
Unlinked trip/trip segment
A journey comprising of a single movement for any travel purpose, including change mode and return home. Distinguished from linked trips by considering changes of travel mode.
Notation

\( \alpha_{inm} \) The probability of alternative \( i \) available to person \( n \) being assigned to joint choice \( m \).

\( \beta \) A vector of taste coefficients to be estimated.

\( C_{nm} \) The set of alternatives available to person \( n \) given their joint choice \( m \).

\( E_{xik}^{pi} \) The direct elasticity of the probability of alternative \( i \) with respect to variable \( k \).

\( E_{xjk}^{pi} \) The cross elasticity of the probability of alternative \( i \) with respect to variable \( k \).

\( f(\varepsilon_{nj}) \) The joint density functions of the unobserved components of utility.

\( G \) The generating function of a specific discrete choice model.

\( i \) A specific alternative.

\( I_m \) The inclusive value of nest \( m \).

\( j \) An alternative.

\( J \) The number of alternatives in a choice set of a decision maker.

\( L(\beta) \) The likelihood function, conditional on coefficients \( \beta \).

\( LL(\beta) \) The log-likelihood function, conditional on coefficients \( \beta \).

\( \lambda_m \) The inclusive value parameter of nest \( m \).

\( m \) A specific nest or subset of alternatives.

\( M \) The total number of nests.

\( n \) A decision maker or person.

\( n' \) A person in the same household or group of person \( n \).

\( N \) The total number of respondents.

\( P_{ni} \) The unconditional probability that person \( n \) chooses alternative \( i \).

\( P_{ni|m} \) The probability that person \( n \) chooses alternative \( i \) conditional on choosing nest \( m \).

\( P_{nm} \) The marginal probability that person \( n \) chooses nest \( m \).

\( \theta_n \) The importance weight of person \( n \) relative to the joint decision.

\( U_{nj} \) The total utility that person \( n \) derives from alternative \( j \).

\( V_{nj} \) The observed component of utility that person \( n \) derives from alternative \( j \).

\( W \) The observed component of utility that varies over nests but not over alternatives within each nest.

\( x_{ik} \) The variable \( k \) entering the utility of alternative \( i \).

\( X_{ni} \) A vector of observed attributes relating to alternative \( i \) and decision maker \( n \).

\( Y \) An argument of the generating function \( G \).

\( y_{ni} \) An indicator, equaling one if individual \( n \) chose alternative \( i \) and zero otherwise.

\( Z \) The observed component of utility that varies over alternatives within each nest.

\( \varepsilon_{nj} \) The unobserved component of utility that person \( n \) derives from an alternative \( j \).
CHAPTER 1. INTRODUCTION

1.1 Background and Research Motivation

A large amount of human activity involves group decisions. For the majority of research in consumer behaviour, the household is frequently regarded as a basic decision-making unit. Members within a household share a variety of household resources including income, time budget, housing amenities, vehicles and play different roles and responsibilities in the household. As a result, preferences and hence choices of individuals within a household are made in the knowledge of the presence and needs of other household members, and thus intra-household interactions are said to exist (Rose and Hensher, 2004; Zhang and Fujiwara, 2006; Timmermans and Zhang, 2009).

In transport research, the individual has conventionally been assumed to be the decision-making unit or the representative agent as most theoretical developments are based on individual behaviour (Zhang et al., 2005). Consequently, studies based on individual decisions have been the dominant theme of transport research. However, both daily activity-travel patterns and long-term decisions can involve group decisions to a lesser or greater degree such as one parent picking up children from school while the other does grocery shopping. For long-term decisions, members of a household will interact and trade between their travel patterns, among other things, to find a location where, for example, the workers may commute further to allow their children to be nearer school. Vehicle ownership and school choice are other examples of long-term group decisions.

Although the importance of household decision-making has long been acknowledged, the development and application of group-based decision models has received interest only recently. Most existing studies assume that an individuals’ influence on household decisions is context-independent. However, different members within a household may have different influences on a household decision, dependent on their preference intensity, experience and personal characteristics. This forces household members to interact in an attempt to reach a consensus. Under these circumstances, travel demand models should incorporate and represent heterogeneous intra-household interactions if they are to reflect reality.

Interactions between household members depend not only on individual characteristics but also on household context and choice situation. Household-specific characteristics such as the presence of a young child can put constraints on the parents and influence the household
travel patterns. Similarly, having flexible working hours may directly or indirectly contribute to the worker’s decision on commuting mode, and thereby to their household’s decisions on the allocation of household resources such as car and time. In other words, travel decisions of a household member are not necessarily independent of the household context and travel behaviour of other members of their household. Thus, there is a need to examine explicitly the roles that household context and choice situation play on intra-household interactions. This thesis aims to fill this gap by investigating intra-household interactions in the observed travel behaviour of household members, using the Sydney Greater Metropolitan Area as a case study.

Within the context of modelling short-term activity-travel behaviour, this research focuses on travel mode choice but incorporates joint household travel arrangements as an outcome of intra-household interactions. Travel mode choices from an individual decision-making perspective have received the most intensive study in the existing literature. In contrast, travel mode choices from the perspective of household interactions remain largely unexplored although the existence of intra-household interactions giving rise to joint activity participation and shared rides is widely acknowledged and is receiving increasing attention (Scott and Kanaroglou, 2002; Vovsha et al., 2003; Bhat and Pendyala, 2005; Timmermans and Zhang, 2009; Auld and Zhang, 2013). However, the evidence limited for a number of reasons including the absence of appropriate data and methodological difficulties. As a result, traditional travel demand models accommodate interdependencies among household members only indirectly through the use of household characteristics as explanatory variables for individuals’ travel behaviour (Bhat and Pendyala, 2005).

More advanced activity-based models are beginning to incorporate explicitly intra-household interactions. 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. These studies have provided a useful but fragmented picture of household interactions in activity-travel behaviour. Moreover, previous studies have mostly focused on time allocation, activity participation, location choice, and car ownership (purchases and disposals) and have paid little attention to travel mode choice despite the way in which mode choice is an important element of operational travel demand models. Thus, there is a gap in the empirical knowledge of the way in which interactions impact upon joint household travel
arrangements for a variety of different activity-travel patterns amongst all household members.

Motivated by the limited understanding of intra-household interactions in individual mode choice behaviour, this thesis investigates the impact of intra-household interactions in detail. Intra-household interactions are hypothesised to exist between/amongst household members regarding car allocation, joint household travel arrangements and mode choice as with other household resources and task allocations already reported in the literature. However, the interactions studied in this thesis are expected to be context-dependent in the sense that household interactions in travel mode choice may depend on individual characteristics, household context, choice situation, and the household’s spatial setting.

With respect to the effect of the household’s spatial setting, or land use patterns in general, previous studies of mode choice behaviour have considered this but their consideration has been mostly at a macro-level and mainly from an individual decision-making perspective. Even though the literature suggests that density, diversity and design are important, it requires a more micro-level approach to better inform transport policies and planning practices for sustainable travel choices. From a household decision-making perspective, it is possible that land use factors at residential and workplace locations influence travel mode choices of all members of the household, not just the worker through intra-household interactions. Improved public transport accessibility at both ends of the work trip, for instance, may increase the probability of using public transport by commuters and consequently increase a partners’ propensity to use car.

In summary, this study aims to explore the role of household interaction, household context, choice situation, and land use factors measured at a micro-level in the context of household decision and travel mode choice. To address these research gaps, this study uses a modelling approach to investigate individual mode choices from the perspective of intra-household interactions taking account of household context, choice situation and spatial setting. The ultimate objective of this study is to understand how evidence on intra-household interactions can provide a better basis for transport policy formulation. The next section summarises the research approach.
1.2 Research Approach

Individual mode choice behaviour is a function of various factors including the level of service (i.e., travel time and travel costs), individual characteristics, and the four elements highlighted above: household interaction, household context, choice situation and land use factors. The existence of intra-household interactions gives rise to joint household activity participation and shared ride arrangements as an effective way of allocating household activities and resources amongst household members to satisfy household and individual needs. The overarching research questions of this thesis are twofold. First, how prevalent are joint household activity-travel arrangements in regional travel demand? Second, what differences do they make to the implications for transport policy? To quantify the effect of intra-household interactions, it is necessary to develop individual mode choice models incorporating joint household travel arrangements. As such, disaggregate data with the information on participating household members are required for the model development, which can be based on individual or group decisions.

In terms of the data, this study develops a procedure to identify joint household activities and travel arrangements from the currently available activity-based travel data. This procedure, described in Chapter 4, can be applied for travel surveys whether a joint travel indicator is collected or not, although it would be simpler if a joint travel indicator such as ‘with whom’ is asked. Data collected by both Stated Preference (SP) surveys and Revealed Preference (RP) surveys can be used for analysing intra-household interactions. However, with respect to mode choice behaviour, SP data are less appropriate as the sample size is usually small because they are expensive to collect and this gives rise to questions about the representativeness of the research results for a specific study area and their transferability, too. On the other hand, secondary data, mainly from travel diaries, usually do not collect information on the travel party and participating household members which are essential elements for analysing intra-household interactions. As a result, the literature has used matching criteria to identify joint household activities and shared rides. Although a matching criteria approach is able to identify joint household activity-travel, some issues remain such as the detection and correction of data inconsistencies, and the extent to which matching criteria may under- or over-estimate occurrences of joint household travel (Kang and Scott, 2011). These issues are discussed and addressed in this research.

Intra-household interactions can be analysed using different modelling approaches including discrete choice models, structural equations models, and multiple discrete-continuous extreme
value models. These models can be implemented in either a probability form or micro-
simulation fashion. This study focuses on intra-household interactions in individual travel
mode choice, and thus the choice of discrete choice models is straightforward. Two modelling
approaches are possible with discrete choice models: one assumes an individual being the
decision-making unit whereas the other a household. The individual-based modelling
approach can incorporate various joint household travel patterns and facilitates predictions
and policy analyses but this approach cannot quantify the influence of each household
member on the joint household decisions. This limitation can be addressed in the group-based
modelling approach which allows different household members playing different roles and
collectively determining behaviour. The sound theoretical underpinning of a group-based
model makes it an ideal modelling approach to use in analysing intra-household interactions
and joint decisions. However, the group-based modelling approach faces the practical
challenge of representing choices of multiple-person households due to a large number of
potential alternatives. Both individual and group-based modelling approaches are considered
in this study.

Intra-household interactions are expected to make a difference to transport policy formulation
and travel demand forecasting. To have insights into the effect of intra-household interactions,
this study undertakes a parallel analysis where mode choice models with and without joint
household travel are developed and their simulation outcomes are compared based on same
scenarios. This is to understand how sizable the under- or over-estimation of the travel
demand would be if intra-household interactions are not directly taken into account. In
addition, joint household travel and mode choices for weekend activity-travel patterns are
investigated and contrasted with weekday patterns. Then, these models are used to perform a
policy analysis which suggests effective transport management measures which tend to be
different between weekdays and weekends for the same purpose of encouraging sustainable
travel choice and reducing traffic congestion.

1.3 Research Contributions
This thesis provides an investigation of intra-household interactions in travel mode choice and
the impact of joint household travel on transport policy formulation and travel demand
forecasting. Both theoretical and empirical models are developed for this thesis and its main
contributions of both scientific and practical relevance are highlighted in this section.
Scientific contributions of this thesis comprise methodological refinements and new
knowledge which will benefit future research in related literature. Practical contributions
relate to the implications for transport policy, planning practice, and travel demand modelling. These two components of the research contributions are summarised as follows.

The scientific component of this thesis contributes to the literature by:

- Testing the relevance of interactions between household members to household mode choice decisions to add an additional ‘layer of interactions’ to activity-based modelling frameworks. The study offers an analysis of household travel decisions embedding context and situation effects, thereby reflecting more realistically the nature of travel decisions (Chapter 2 and Chapter 6).
- Using a comprehensive set of variables to explain individual mode choice behaviour. In particular, a model developed in this thesis integrates four elements influencing individual travel mode choices: intra-household interaction, household context, choice situation, and land use factors measured at the micro-level alongside the level of service and other determinants identified in the literature. While some of these factors are included in previous studies, no existing model possesses them all (Chapter 6).
- Deriving a generalised Parallel Choice Constrained Logit (gPCCL) model to take account of multiple players in a joint decision. The use of allocation parameters in the gPCCL model allows an individual choice belonging to multiple joint household choices, and thus provides a more flexible means of investigating group decisions involving more than two persons. Although the estimation with mode choice decisions did not converge, this model is useful for studying one-off decisions such as residential location choices and household vehicle ownership (Chapter 3).
- Developing a systematic typology of tours that helps in differentiating tours based on tour structure and the implied intra-household interactions. This tour typology can be extended to match with other dimensions such as the travel party size, activity type and tour complexity, depending on the purpose of a specific study (Chapter 4).
- Providing both algorithm and graphical methods for detecting and correcting data inconsistencies in identifying joint household activity and travel from the travel diary data (Chapter 4).
- Developing a new approach to classify tour complexity which takes into account not only the number but also the spatial distribution of activities chained into a tour. The new approach considers tours with multiple purposes at a single destination as a separate tour type and relates tour complexity to the travel mode. This approach gives clearer and more significant relationships between tour complexity and mode choice, explaining the reasons why findings in the existing literature conflict (Chapter 5).
• Examining the joint household travel arrangements and mode choices for weekends and contrasting these with weekday patterns. The weekend joint activity and travel patterns have been studied in the literature but this has been limited to descriptive analysis with few attempts have been made to specify mode choice models for weekend joint household travel (Chapter 5 and Chapter 6).
• Performing a parallel analysis where mode choice models with and without a joint household travel dimension are developed and compared for a better understanding of the impact of joint household travel. Through a comparison of simulation outcomes, this thesis adds to the literature the conditions that lead to the overestimation and underestimation of the traveller’s response to changes to transport policy and the level of services when joint household travel is ignored (Chapter 6).

The practical contributions of this thesis are as follows.
• Understanding the impact of household interactions on travel behaviour gives a strong signal as to the way in which policy outcomes occur (Chapter 6).
• The empirical comparison of joint household travel across countries shows the importance of modelling joint household travel for a better travel demand forecasting and a more credible analysis of transport policy. Whichever unit of analysis (trip, tour, daily activity pattern) or modelling framework (four-step modelling vs. activity-based modelling) is used, joint household travel accounts for a substantial proportion of regional travel, and therefore, constitutes a fundamental aspect in understanding travel behaviour (Chapter 5).
• The detailed process of constructing joint household travel datasets from the currently available household travel survey improves its usefulness in studying intra-household interactions and joint household decisions. Findings from this process also suggest improvements to the design, validation and implementation of activity-travel surveys to allow better data to be collected (Chapter 4).
• The empirical models of individual mode choices with joint household travel arrangements on weekdays and weekends can be used to assess and evaluate different transport management measures such as the introduction of high occupancy vehicle/toll lanes, public transport fares for group travel, parking restriction at the workplace, and improvement to the level of public transport services. Using these models as a simulation tool, the effects of different transport management measures on promoting public transport use and reducing traffic congestion can be compared for the selection of a more effective measure (Chapter 6).
Empirical investigation of the impact of various land use factors on mode choices identifies measures that are most likely to support policy change for sustainable transport choices. The use of a micro-approach to measure land use patterns at both origin and destination for this investigation provides evidence to support transport policies and planning practices (Chapter 6).

The differences between weekdays and weekends in terms of the proportion of joint household travel, shared activities, and value of time savings provide critical inputs into the choice of appropriate transport management measures on weekdays and weekends (Chapter 5 and Chapter 6).

### 1.4 Outline of the Thesis

The remainder of this thesis is organised into six chapters. The present chapter has provided an introduction to intra-household interactions in transport research and highlighted the motivation and contributions of this study. In very broad terms, the research approach taken in fulfilling the research objectives has been presented. The contents of the following chapters are outlined next.

Chapter 2 begins with a review of the literature on travel mode choice and discusses the current issues in mode choice modelling. This discussion points to the way in which most existing studies of mode choice behaviour are based on an individual decision-making mechanism with intra-household interactions being ignored. The chapter then reviews the literature on group decisions and intra-household interactions. How intra-household interactions influence the way in which decisions are made is expounded and empirical findings are drawn upon to argue for why the study of intra-household interactions is important. Various analytical techniques and data requirements are discussed to show how intra-household interactions can be handled. Drawing on this review, research gaps are identified and research hypotheses are framed and discussed in terms of how this thesis can contribute to the literature.

Chapter 3 introduces the study area and describes the available data sources for testing the thesis hypotheses. This chapter begins with a broad description of the study area to provide a context for the current study. This is followed by a detailed description of the data including travel survey data, transport network data and land use data. The analytical concepts and models proposed to test the research hypotheses are then presented. The chapter ends with an
evaluation of two modelling approaches (individual-based vs. group-based) where their advantages, disadvantages and data requirements are highlighted.

Chapter 4 presents steps taken to transform the travel diary data of the study area into the datasets that are required for modelling intra-household interactions and testing the research hypotheses. This process involves three steps of identifying joint household trips, detecting and correcting data inconsistencies, and transforming a trip-based dataset into a home-based tour dataset for joint tour pattern identification. The chapter describes the principles and the assumptions employed for the identification of joint household travel in the presence of data inconsistencies, which can be detected by both algorithm and graphical methods. The chapter provides a typology of joint tours which represent nine different ways of arranging household activities and travel into a home-based tour. Each of the nine joint tour patterns is discussed before presenting their rates of occurrence from the constructed tour-based dataset. The chapter then summarises the different datasets, their attributes and discusses the differences between them, setting the scene for Chapter 5 where descriptive statistics are presented.

Chapter 5 presents a series of descriptive analyses as a precursor to modelling individual mode choices with joint household travel arrangements. The chapter presents the different datasets created in Chapter 4 to provide the overall share of joint household travel where different units of analysis are used including trip, home-based tour and daily activity pattern. By comparing the results with those from previous studies, this chapter draws a general picture of joint household travel and highlights its importance in understanding travel behaviour and analysing transport policy. In addition, statistics are provided separately for weekdays and weekends which highlight significant differences in joint household activity and travel. A deeper analysis is then conducted, using the home-based tour dataset, to explore the motivation for and constraints on joint household travel and travel mode choice. This analysis identifies predictors that need to be incorporated in the modelling and the implications for modelling individual mode choices with joint household travel arrangements.

Chapter 6 presents the estimation results of the empirical models for both weekday and weekend travel. The chapter first discusses the specification of group-based and individual-based models, their dependent and explanatory variables as well as the decision-making units and the simplifying assumptions employed for model development. The estimation results are then interpreted and validated by comparing with similar model analyses. The models are used to perform ‘what-if’ scenarios where changes to modal share are simulated to provide a
better understanding of the impact of joint household travel on policy formulation. A parallel analysis is also conducted in this chapter where estimation results and simulation outcomes of a model without joint household travel are presented and compared against those from a model incorporating joint household travel. This provides an understanding of the practical impact of ignoring intra-household interactions in policy formulation.

Chapter 7 concludes the thesis and provides an overview of intra-household interactions in travel mode choice and summarises the findings of this study. The chapter discusses the practical relevance of the research findings with implications for transport policy and planning practices being detailed. The original contributions of this research are highlighted, before acknowledging the limitations of this thesis and making of suggestions for future research.
CHAPTER 2. LITERATURE REVIEW

Chapter 1 has provided the research background of this study and identified the issue of intra-household interactions in individual travel behaviour. Recognition that individuals do not make their travel decisions in isolation of the household context has produced a growing interest in intra-household interactions and group decision-making. A variety of approaches to investigating joint household decisions have been explored by different research fields. The objectives of this chapter are to review those works most relevant to travel decisions and identify the research gaps, the modelling approaches and the data requirements for the current study. Chapter 1 has also highlighted the potential effect of land use patterns on travel behaviour via interpersonal interaction mechanism. The present chapter therefore elaborates upon this discussion with a focus on mode choice and a way in which land use patterns have been measured and used in existing travel demand models.

This chapter is organised into six sections with each section ending with an identification of research gaps that lead to the generation of the research hypotheses of this study. The chapter begins with a brief review of determinants of travel mode choices and summarises current issues in mode choice modelling. Section 2.2 discusses the decision-making units in transport research and is orientated towards the context of travel mode choice and household decision study. How decisions are made by households with a focus on empirical findings and analytical techniques are reviewed in Section 2.3. The relevance of heterogeneity in group decision-making is highlighted in Section 2.4. Section 2.5 summaries the data requirements and the modelling approaches used in the literature to investigate intra-household interactions. These latter three sections inform the methodology for this study. Finally, Section 2.6 synthesises the research gaps and identifies the research hypotheses for this study.

2.1 Determinants of Travel Mode Choice

Mode choice analysis has a rich literature as this outcome of travel decisions plays an important role in the formulation of transport policies and planning practices. Mode choice is one of the classic travel decisions that received a substantial attention in early development and application of discrete choice models (Ben-Akiva and Lerman, 1985). However, most existing studies of travel mode choices are individual-based with only few studies analysing this travel behaviour from a household decision and interpersonal interaction perspective. More advanced models are beginning to explicitly incorporate intra-household interactions and mode choice modelling continues to be active in transport research as seen by a special
issue of *Transportation* (Abou-Zeid and Scott, 2011) as well as studies found elsewhere. This section reviews evidence on the determinants of travel mode decision from studies using individual-based analysis and sections that follow look at household decisions and joint travel. The collective body of research on mode choice behaviour has revealed a number of determinants that can be broadly classified into socio-demographic characteristics, level of service attributes, and land use patterns with the first two sets of determinants being commonly referred to as social-economic factors.

2.1.1 Social-economic characteristics

A wide range of factors representing socio-economic characteristics was examined in the literature on mode choice decisions. Travel time, travel cost, household income, car availability, household size, the number of workers, the presence of children and other variables characterising household life cycles were consistently found to be highly correlated with travel mode choice decisions (Cervero and Kockelman, 1997; Hess, 2001; Cervero, 2002; Chatman, 2003). In addition, some of these factors were found to be more significant than others in driving travel mode choice. The best way to look at the relative importance of influencing factors on travel demand is through the concept of ‘elasticity’. In its simplest form, the elasticity of a factor is the ratio of the proportional change in travel demand to the proportional change in that factor. Elasticities vary over time and therefore, it is a common practice to distinguish short run from long run elasticities. There is no consensus about short run and long run definitions but most studies consider short run as 1 or 2 years and long run to be around 12 – 15 years (Paulley et al., 2006). There exist some meta-analyses of public transport demand and value of travel times which offer evidence on the importance of socio-economic characteristics to travel decisions. The main outcomes of these studies are summarised below.

A meta-analysis conducted by Paulley et al. (2006) highlighted the effect of fares, quality of service, household car ownership and household income on travel demand. With respect to urban travel, this study found that public transport fare elasticity ranges from −0.3 to −0.6 in the short run with a little difference across public transport modes. These elasticities suggest that a 1% increase in public transport fare will result in a 0.3% to 0.6% decrease in public transport use in the short run. Similarly, the review suggested in-vehicle time elasticity to be in the range of −0.4 to −0.6 while the generalised cost (combining in-vehicle, walk and wait times) had an elasticity range of −0.4 to −2.0. Other attributes characterising the quality of service including interchange, reliability, waiting environment and the availability of
information are less evident in terms of demand elasticities. In addition, effects of these
factors on travel demand cannot be treated in isolation of each other due to collinearity
(Balcombe et al., 2004). This is particularly true for the effects of household income and car
ownership. Income has a positive influence on public transport demand but is offset by a
negative impact through its influence on car ownership. Paulley et al. (2006) found that
income elasticity of bus demand, including the indirect effect of car ownership, was in the
range between 0 to –0.3 in the short run, with somewhat higher values in the long run.

Another meta-analysis reported by Holmgren (2007) draws a similar picture of public
transport demand elasticities. Using data from 81 studies, Holmgren estimated fare elasticities
ranging from –0.009 to –1.32 with an average value of –0.38. This is consistent with the result
of Paulley et al. (2006) reported above. As usual, this study found that income elasticities of
public transport demand were less certain with a large range between –0.82 and 1.18 and a
mean value of 0.17, based on 22 observations. This study also pointed out that the problem
with income elasticities may originate from changes in modal choice with public demand
being highly sensitive to the level of car ownership (elasticity range of 0 to –3.37 with a mean
value of –0.86, based on 8 observations). The report recommended that fare, car ownership,
quality of service, income and fuel price should ideally be included in travel demand models
alongside other explanatory variables. Balcombe et al. (2004) provided a full discussion on
the relationship between public transport demand and these factors and came to the same
conclusion that fare, quality of service and car ownership are the most significant drivers of
public transport demand.

2.1.2 Land use patterns

While it is acknowledged that travel mode choices depend on both socio-economics and land
use patterns, the former has been identified as having stronger impact (Ewing and Cervero,
2001). The impact of land use patterns, which are characterised by population and
employment density, accessibility to central business district or local centre, the availability of
public transport, and other built environment factors at the place of residence and the place of
work, on travel behaviour were not always found to be significant (Handy et al., 2005;
Chatman, 2008; Tracy et al., 2011). More specifically, evidence on the relationship between
land use and travel are mixed and dependent on which aspects of the land use pattern and
travel behaviour are being measured. This is discussed further below.
The review by Ewing and Cervero (2001) showed that travel mode choice was most affected by local land use characteristics out of the four key transport ‘outcomes’ of trip frequency, trip length, travel mode choice, and vehicle kilometre travelled (VKT). They also found public transport and non-motorised mode use depended primarily on development densities and secondly on the degree of mixed land use. Similarly, car use was consistently found to be affected by residential density and the degree of mixed land use with the effect of local land use patterns being only marginal, as compared to regional accessibility and socio-economics (Cervero, 2002; Handy et al., 2005; Ewing and Cervero, 2010).

Generally, the effect of land use patterns at the place of residence on travel mode choices were captured by the three core dimensions or 3Ds: density, diversity, and design (Cervero and Kockelman, 1997). Density measures how intensively land is used for housing, employment, recreation, and other purposes. Diversity reflects the degree of mixed land use while design represents street network layout and the quality of cycling and walking environment (Cervero, 2002). A meta-analysis conducted by Ewing and Cervero (2010) suggested average elasticities of public transport use with respect to density, diversity and design were 0.07, 0.12 and 0.29 respectively. Although the effect of each land use factor on public transport use is small, a composite elasticity created by a combination of these values may be large enough to be considered for policy interventions. Another justification for including these measures of land use patterns is that they significantly improves predictive power of travel demand models (Ewing and Cervero, 2010).

Studies showed travel mode choices were also affected by the land use patterns at destinations, the fourth “D” of the built environment (Tsai, 2009; Ewing and Cervero, 2010). For public transport and walking modes, the employment density at destinations was as important as, if not more important than, population density at residential locations (Ewing and Cervero, 2001). Ewing and Cervero (2010) found the average elasticity of walking with respect to employment density was 0.15 for the place of destination, as compared to 0.04 for the place of residence. For the car mode, employment density at the place of work was inversely correlated with the likelihood of car commuting (Chatman, 2003). Also, public transport proximity to the workplace has a stronger effect on commute mode choices than its proximity to the place of residence (Tsai, 2009). The other dimensions of the built environment at destinations – except for parking treatments discussed below – had only marginal effects on primary trips, e.g., commute trips (Ewing and Cervero, 2001). However,
they played a more important role in secondary trips, i.e., those trips within an activity place that can be made either on foot or car (Ewing and Cervero, 2001; Chatman, 2003).

Parking treatments including parking availability, parking cost, and parking lot locations have been shown to be important determinants of travel mode choices both for non-work and work trips (Cervero and Kockelman, 1997; Hess, 2001; Cervero, 2002). The location of parking relative to a shop entrance (e.g., at the rear of the shop) has an impact on the accessibility to the shop generally (Cervero and Kockelman, 1997). Also, having to pay to park a vehicle was found to be highly inversely correlated with the likelihood of using private car as a travel mode for any travel purposes (Cervero and Kockelman, 1997; Hess, 2001). Finally, parking cost was found to have a strong influence on commuting mode choice decisions (Hess, 2001).

Due to data limitations, especially land use patterns at the place of destinations, most existing studies on the effect of the built environment at trip destinations on travel mode choices focus on commuting trips (as opposed to non-work or secondary trips) because the destination locations and land use characteristics for these are more easily collected. Secondary trips, which can be made either on foot or by car from the destination of a primary trip, may not be reported by many respondents in surveys relying on travel diaries, leading to underestimation of the relevance of urban form at destinations (Ewing and Cervero, 2001).

A common element to most of these studies is that the effect of land use patterns on travel mode choice has been analysed using unlinked trips that ignore the fact that individual trips are made in sequence and these trips collectively (as opposed to independently) influence the way in which travel decisions are made (Frank et al., 2008; Shiftan, 2008). For example, a worker will usually not drive back home from work if they have travelled to work by public transport. Similarly, workers may commute by car in order to drop-off/pick-up their children at school en route to/from work. This phenomenon is known as trip chaining and is better analysed using a tour-based framework. The tour-based analysis links individual trips together and treats travel as a round journey (commonly known as a tour) that starts and ends at the same location. The tour-based approach has demonstrated to be superior to the trip-based approach in analysing the relationship between land use patterns and travel behaviour (Krizek, 2003; Shiftan et al., 2003; Shiftan, 2008).

The evidence from the tour-based analysis on the relationship between land use patterns and travel behaviour are increasing but still limited. Krizek (2003) found that households with
higher levels of neighbourhood accessibility (measured by a combination of density, land use mix and street patterns) made more tours with fewer stops per tour. The effect of neighbourhood accessibility on the generation of household tours was also found to be different across travel purposes and levels of tour complexity. However, the study did not consider mode choice as one dimension of tour characteristics and therefore offered no evidence on the relationship between land use patterns and mode choice decisions.

With respect to mode choice decision, Frank et al. (2008) found that higher levels of land use mix, residential density, street connectivity, and retail density increased walking, cycling and public transport while reduced driving alone for all travel purposes. Similarly, Shiftan (2008) using an extended Portland activity-based model found that an improved accessibility resulting from a package of sustainable land use – transport policies increased the number of public transport tours by about 5%, and walking and cycling tours by about 7% each. However, this improvement to accessibility and public transport level of service also increased the number of car tours by about 2.5% and the vehicle kilometre travelled by 1.4%. Shiftan explained this unexpected result by the way higher number of activity opportunities and the cheaper cost of accessing them allowing people to split a day-long tour into two or more shorter tours. This highlights the advantages of a tour-based approach over a trip-based approach which does not have such capacities in analysing the relationship between land use patterns and travel choices (Shiftan, 2008).

An important caveat to the relationship between land use patterns and travel behaviour is whether the observed difference in travel behaviour of people residing/working in different land use patterns are due to the land use configuration itself or whether this is a result of the individual’s preferences for a particular travel option. This is referred to as the self-selection phenomenon whereby people with different travel preferences choose to live or work in the type of neighbourhood that supports their travel preferences. This can be addressed by controlling for individual attitudes towards residential location choices and travel preferences with the use of attitudinal data in the cross-sectional research or the ‘before and after’ data in the intervention-based approach, once a change to land use has been introduced (TRB, 2005; Mokhtarian and Cao, 2008). The review by Cao et al. (2009) suggested that residential self-selection did exist but the effect of land use on travel behaviour was significant and independent of residential self-selection. However, other studies have found that neighbourhood type had a marginal effect on travel behaviour when individual attitudes, lifestyle and socio-economic characteristics were controlled for (Crane, 2000; Boarnet and
Crane, 2001; Zhang, 2005). Overall, there is no consensus about the causal inference in the relationship between land use, attitude, and travel behaviour. What is consensus among researchers is the limited understanding of the complex relationships among land use patterns, individual’s preferences and travel decisions.

Another concern to the relationship between land use and travel is that most existing studies are based on an individual decision mechanism. From the perspective of joint household decision, to what extent the land use patterns influence household travel mode choices remains largely unknown. A shift from car to public transport of a household worker due to an improvement to public transport accessibility may mean the availability of the household car for the household non-workers to use. The non-workers’ induced travel demand for the household car may in fact cancel out the effect of the improvement to public transport for the worker, leading to a marginal effect of changes to land use patterns on the net travel outcome. With respect to intra-household interactions, the initial findings of studies on the allocation of household tasks (as opposed to travel decisions) suggested that, although interactions within a household did not take place in a geographical vacuum, land use characteristics at the place of residence had a smaller impact than socio-demographics (Schwanen et al., 2007). Whether this relationship holds for household travel arrangements is still an open question. To ascertain whether land use policy is an effective way to change travel behaviour, it is necessary to investigate the relative influence of spatial attributes and socio-economics from the household decision-making perspective.

2.2 Decision Making Units in Transport Research

Studies based on individual decisions have dominated research in transport, although the influence of other people on these individual decisions has long been acknowledged, whether these are the decision maker’s household members, friends, colleagues or employers (Thorndike, 1938; Davis, 1976; Timmermans et al., 1992; Rose and Hensher, 2004). Earlier studies of household travel behaviour have only implicitly examined intra-household interactions by specifying household characteristics as part of the individual utility function but this neither reflects interdependencies between household members nor ensures consistency of model outcomes (Timmermans, 2009). Only recently have researchers paid attention to household decision-making in transport research (Bhat and Pendyala, 2005; Timmermans and Zhang, 2009).
Choices of travel mode, travel time, travel distance, residential location, activity participation, workplace location of multiple-worker households, and the allocation of household resources and tasks are all, more or less, based on group decisions (Bhat and Pendyala, 2005; Rich and Nielsen, 2001; Roorda et al., 2009; Timmermans, 2009; Zhang et al., 2009). Members within a household physically share various household resources such as income, time, amenities and housing, and play different roles in the household (Timmermans and Zhang, 2009). Consequently, individual decisions may take the presence and needs of other household members into account giving rise to intra-household interactions. In other words, household members allocate and distribute household resources, tasks, and activities among each other to meet household and individual needs under social, spatial and resource constraints. A parent may have to take a day off work to take care of an ill child; a family may agree to participate jointly in a weekend recreation activity; or workers may commute by public transport to free the family car up for their partners escorting their children and running household errands.

The existence of intra-household interactions suggests that travel demand models should look at household travel behaviour from the household decision-making perspective where intra-household interactions are explicitly taken into account. Early activity–travel models considered travel demand generated at the individual level using household characteristics as explanatory variables, without direct regard to the existence and influences of other household members (Bhat and Pendyala, 2005). There appears to be increasing interest in transport research dealing with joint decision-making although theoretical and empirical studies are still rather limited (Timmermans, 2009). The next section reviews studies in the transport literature looking at intra-household interactions.

2.3 Intra-Household Interactions in Transport Research
The existing literature on intra-household interactions can be broadly classified into two groups based on the long-term or short-term nature of the household decision in question. Although a methodological classification could be used, it is the differences in the nature of the choices (long-term or short-term, one-off decisions or repeated decisions) that lead to the use of different methods for studying intra-household interactions. Transport-related decisions that require intra-household interactions and long-term commitment include residential location, car ownership, and school location choices while short-term decisions include daily activity-travel patterns, joint household activity participation, household car allocation and use, ride-sharing and chauffeuring arrangements. The following subsections examine these
studies by topic from the perspectives of empirical finding, travel mode choice and analytical technique of intra-household interaction. Grouping studies by their topics helps identify the areas where intra-household interactions have been studied in the literature. This is also relevant to the way in which intra-household interactions are implemented in practical travel demand models where travel decisions are broken down and modelled in a particular sequence due to the complexity of travel behaviour. The literature has examined four inter-related topics relating to intra-household interactions from the viewpoint of activity-based travel behaviour and time use. These are car ownership and mode choice, residential location choice, household task and time allocation, and activity generation and scheduling.

2.3.1 Car ownership, transaction, and travel mode choice
Although there are many studies on car transactions (i.e., purchase, disposal, replacement) and car ownership and use, very few studies have analysed these travel behaviours from a household decision perspective. Only recently have researchers begun to consider the relevance of incorporating intra-household interactions into car ownership, transaction, and use behaviour (Maat and Timmermans, 2007; Roorda et al., 2009; Timmermans, 2009; Zhang et al., 2009). Using revealed preference (RP) data, these studies consistently confirm the existence of intra-household interactions on household decisions regarding vehicle ownership and transactions. Table 2.1 summarises the context, sample and modelling approaches of these studies with each of them being discussed further below.
Table 2.1 Overview of studies on intra-household interactions in car ownership and use

<table>
<thead>
<tr>
<th>Study</th>
<th>Sample</th>
<th>Travel-related decision</th>
<th>Method</th>
<th>Ways of incorporating household interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maat &amp; Timmermans, 2007</td>
<td>729 households; Netherland</td>
<td>Number of household cars</td>
<td>MNL</td>
<td>Commute distances and urban forms at the workplace(s) of working partner(s)</td>
</tr>
<tr>
<td>Zhang et al., 2009</td>
<td>436 couples; Hiroshima, Japan</td>
<td>Car engine displacement</td>
<td>Latent Class model</td>
<td>Group utility function; Individual weights</td>
</tr>
<tr>
<td>Roorda et al., 2009</td>
<td>547 households; Toronto, Canada</td>
<td>Car transaction (add, replace, dispose, do nothing)</td>
<td>Simulation</td>
<td>Use of 'stress' measures to reflect conflicts experience by household members in activity-travel</td>
</tr>
<tr>
<td>Anggraini et al., 2008; 2012</td>
<td>3,523 car-deficient households; Netherlands</td>
<td>Car allocation between the household heads for work/non-work episodes</td>
<td>Rules based decision tree</td>
<td>Use of a decision tree induction method to formulate 'individual dependent condition - action' rules</td>
</tr>
<tr>
<td>Miller et al., 2005; Roorda et al., 2006</td>
<td>4,049 households; 8,603 tours; 19,335 trips; Toronto, Canada</td>
<td>Mode choice</td>
<td>Simulation</td>
<td>Car allocation; Joint travel arrangement; Drop-off/pick-up arrangement; Total household utility</td>
</tr>
</tbody>
</table>

Interactions between partners in car ownership behaviour were indirectly investigated through the effects of urban form at the workplace(s) of working partner(s), and through commute distance by each worker in the dual-earner households in Maat and Timmermans (2007). They found that the urban form at work location moderately influenced intra-household interactions while commute distance did not show any observable effect. Using a latent class modelling approach to analyse household vehicle type choice behaviour, Zhang et al. (2009) found that intra-household interactions and member relative influence were highly significant, where the latter was dependent on member specific characteristics such as age, job status and car main user indicator. More importantly, this study found that heterogeneity did exist in household decision-making rules. Adopting micro-simulation, Roorda et al. (2009) examined the household interactions in vehicle allocation through the concept of “stress” resulting from conflicts experienced by household members arising from the limited number of vehicles alongside household members having concurrent but independent activities. The study found that measures of activity-travel stress, signalling intra-household interactions, were among the significant predictors of household vehicle transaction and vehicle type choice behaviour.
Using data from the Mobility Research Netherlands survey and focusing on work activities, Anggraini et al. (2008) derived decision rules for the car allocation decision in car-deficient households (i.e., households with fewer cars than drivers), using a decision tree induction method. Characteristics of the household heads and their work-related activities (number of work episodes, duration and schedule), household composition, age of the youngest child in the household, and accessibility to workplaces of each worker by car and bicycle were used as condition variables to formulate car allocation decision rules. The study found that temporal separation between home and workplace, measured as car travel time and car accessibility relative to bicycle accessibility, played the most important role in car allocation decisions of car-deficient households. Also, the impact of household socio-demographics on household car allocation was identified as significant but to a much lesser extent. Similar results were found for non-work activities in a recent study by the same authors (Anggraini et al., 2012).

Miller et al. (2005) and Roorda et al. (2006), using a simulation technique, developed a tour-based mode choice model for the Greater Toronto Area, Canada to generate the travel mode for each trip of an individual’s home-based tour. The model explicitly recognised household interactions through vehicle allocation and joint household travel arrangements within the three-step modelling processes. First, mode choice for individual and fully joint tours were determined without regard for the availability of household cars; then it was decided which household member was to use the car if conflicts occurred in which more than one household member sought to use the same car at the same time; finally, whether ridesharing opportunities existed within the household was evaluated in terms of total household utility. Implicit in these models was the assumption that an individual’s mode choice decisions come first, then joint household travel decisions. However, it might be that the decision hierarchy is the other way around: household members choose their travel modes conditional on the joint household travel decisions. Further, serve-passenger travel (to accompany or provide a lift to someone) in these models is assumed to be made by car only and allocated directly to the passenger’s activity. This assumption effectively 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). A further concern with this micro-simulation approach is the computational burden associated with the estimation of parameters.

Table 2.1 highlights a variety of approaches to incorporating intra-household interactions in the household car ownership and use decisions. Some approaches are able to quantify the
individual power in the household decisions. The individual power in joint household decisions has been found to be significant, although it has been treated as constant (e.g., Zhang and Fujiwara, 2006) or at most a function of individual-specific characteristics (e.g., Zhang and Fujiwara, 2009). Schwanen et al. (2007) argued that the relative influence should be specified as a function of household and its member attributes, and even of the land-use characteristics to represent better the heterogeneity in household decision-making and the role of the built environment on intra-household interactions, respectively. Ferdous et al. (2011) developed a hazard-based model taking into account familial, social, and spatial contexts to describe the duration of walking and cycling activity as a measure of non-motorised mode use. They found that heterogeneity effects due to unobserved individual, household, social and spatial factors were all significant. Household-specific effects constitute the family influences that may be attributed to lifestyle choices at the household level, intra-household interactions and parental influence. Sidharthan et al. (2011) investigated the effect of parental influence on their children’s travel behaviour and found if the parents travel behaviour was classified as ‘active’ (cyclists or walkers), this increased the probability of children using the corresponding modes for school trips, although the influence was not significant. They also found that parental attitudes towards walking or cycling as the means of their children’s travel mode between home and school significantly influenced the use of the walk mode by their children for school trips. This suggests that the heterogeneity within households may also be a result of attitudes.

Studies directly analysing car use and travel mode choices from the perspective of household interaction are scarce (Maat and Timmermans, 2007) apart from few comprehensive activity-based simulation models, e.g., TASHA (Roorda et al., 2009) and ALBATROSS (Arentze and Timmermans, 2004) where car allocation and mode choice decisions were used as feedback in the models. Given that vehicle allocation and travel mode choice are important aspects in transport research, more theoretical and empirical studies incorporating household decisions are needed to provide additional insights into travel mode choice behaviour.

2.3.2 Residential location choice
The study of intra-household interactions in transport-related fields has been led by Timmermans and colleagues, who have used a hierarchical information integration (HII) method (a form of stated preference (SP) approach) to examine the role of transport facilities on residential location choice (Timmermans et al., 1992; Borgers and Timmermans, 1993). In the first stage, attributes influencing residential preference and choice were identified and
clustered into some higher-order constructs (i.e., major categories). Each partner of the household was separately required to score the combinations of attributes for each higher-order construct and for each residential location alternative. Statistical models were then employed to calculate the contributing scores of original attributes to each higher-order construct. In the second iteration, partners were asked to jointly evaluate and choose one alternative in each choice task, in which the design used the scores of the higher-order constructs obtained in the first stage. An assumed multinominal logit choice model was used where the joint utility of the couple was specified as additive to analyse the influence of these higher-order constructs on choice behaviour and trade-offs in the couple’s preferences for these higher-order constructs. Using a sample of dual earner households in the Netherlands, they found that attributes were weighted differently in forming individual preferences (first stage) and the couple’s joint decision-making (second stage). Specifically, while each partner as an individual attached more weight to the residential attributes, the joint decision-making was more heavily influenced by job situation. From a group decision perspective, these studies found that transport facilities marginally influenced residential location choice. The relevance of travel mode to residential choice was indirectly investigated through attributes characterising the proximity to public transport and its frequency (Timmermans et al., 1992) or access to transport facilities and travel time to work by different modes (Borgers and Timmermans, 1993). Effects of these attributes were either not significant or small in magnitude and confusing in sign, suggesting an unimportant role of travel mode in household residential decisions.

Using a before and after joint decision-making SP survey of 156 married couples in Hiroshima, Japan, Zhang and Fujiwara (2009) showed 40 percent of the household members changed their stated choices of residential relocation with joint decisions, and that intra-household interaction significantly contributed to household utility. This suggests the importance of intra-household interactions in bringing about more consistency in predicting household travel behaviour. The study found that access to local facilities and city centre are influential factors, along with other factors of socio-economics, of the intention to move home and choice of location. The study also found that intra-household interaction indeed changed household total utility, and that each member’s relative influence was affected by gender and age.

The impact of gender and age in the influence of a household member relative to others on the household decision-making was investigated by Abraham and Hunt (1997). They modelled
the interaction between location choices (home and workplace) and mode choices using a nested logit model with a variable nesting structure to allow the travel mode of one household worker to influence the overall household utility more than those of others. The empirical analysis using a sample of 961 households in Calgary, Canada found that the scaling factor (i.e., nesting factor) was significantly larger for female members of the set while the effect of age appeared to be insignificant. This suggests that the travel conditions for the female members of the household are more important than those of the male members in the household decision-making. The model combined all three interrelated choices into one joint household decision, although the empirical results showed some suspect estimates (e.g., very low value of travel time and walking and waiting is less onerous than riding public transport). This might be because the model did not consider the trade-offs between work and non-work travel on the household’s residential choice.

A common element to these studies is the use of a group utility function to model joint household decisions. These studies treat the household as the decision-making unit with household members collectively determining household behaviour. Given the long term commitment of the entire household to the residential location, the group-based approach seems to be appropriate. This may not necessarily be the case for travel decisions that are short term in nature. Moreover, short term decisions made by household members are not always mutually exclusive, raising difficulties in aggregating individual utilities into the household utility so as to apply the group-based approach. This is discussed further in Section 2.5.

2.3.3 The allocation of household tasks and resources

The study of intra-household interactions has been investigated in the context of household task allocation and time use. Early theory of household time allocation owes its development to the work of Becker (1965) who treated a household as though it were an individual with a utility function comprising of the aggregated amounts of time and goods of the household, and a pooled time and monetary budget. Adopting this modelling framework, Fujii et al. (1999) used a structural equations model to study how an individual allocated time to in-home and out-of-home activities with other household members, non-household members and alone. Their analysis indicated that the time spent in joint activity with other household members, particularly with children, was important to individual feelings of satisfaction and in daily travel patterns. This highlights the importance of studying joint activities and travel
between adults and children, an important aspect of intra-household interactions that remains largely unexplored.

Becker’s modelling framework has been criticised for ignoring intra-household interactions and dealing with joint decision-making as a ‘black box’. To overcome this problem, Zhang et al. (2002; 2005) developed household time allocation models where group decisions were explicitly incorporated through the use of a household utility function. The models, however, incorporated only time constraints with respect to each household member. Based on this framework, Kato and Matsumoto (2009) proposed a Tobit-type joint time allocation model with three refinements over the previous studies. First, the model was concerned with a nuclear family with a representative child. Second, it considered not only time constraints but also the monetary budget of the household. Third, the model explicitly reflected the occurrence of an activity by using a non-linear Tobit-type modelling approach. The associated empirical study compared the intra-household interactions between a weekday and a weekend day, and between two different cities. Using a similar modelling approach, Wang and Li (2009) developed a model of time allocation in a household with the external help of a domestic helper. Intra-household interactions were reflected through the contribution of all household members’ incomes to cover helper-hiring costs, and through the trade-offs between hiring fee and time for maintenance activities which is otherwise dedicated for sharing household responsibilities.

Table 2.2 summarises the main findings alongside the empirical samples and estimation methods of time use studies with intra-household interactions. These studies confirm that intra-household interactions exist and that the influence of different household members can be identified and are statistically significant in almost every single empirical study concerning household resource allocation and time use. These findings suggest that using information from a representative member to analyse household decisions regarding travel behaviour, as many traditional methods do, may result in misleading conclusions. In this regard, research in other disciplines have found that male and female preferences differ, and that neither of the couples’ individual preferences reflect the outcome of the household decisions appropriately, even though female preferences appear to be a better proxy than those of males (Dosman et al., 2001; Dosman and Adamowicz, 2006). For example, only in approximately 40 percent of cases does one spouse’s or partner’s preferences provide an accurate measure of household decisions about vacation locations (Dosman and Adamowicz, 2006). Together, these findings suggest the use of activity-travel data from the entire household for analysing household
decisions and joint travel arrangements. Incorporating interactions amongst all household members in travel demand models is methodologically difficult. This is evidenced in Table 2.2 where all but one suggested approach is for the household heads. The exception is the study by Kato and Matsumoto (2009) where three household members are considered in modelling instead of the two household heads but this approach is not extendable to handle the entire household.

Table 2.2 Summary of time use studies with intra-household interactions

<table>
<thead>
<tr>
<th>Study</th>
<th>Sample</th>
<th>Travel-related decision</th>
<th>Method</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fujii et al., 1999</td>
<td>204 persons; Osaka-Kobe, Japan</td>
<td>Trip frequency and trip time</td>
<td>Structural Equations Model (SEM)</td>
<td>Time spent in joint household activity, particularly with children, is important to individual feelings of satisfaction and in daily travel patterns</td>
</tr>
<tr>
<td>Zhang et al., 2002; 2005</td>
<td>188 two-person households; Rotterdam, Netherlands</td>
<td>Time spent on in-home, independent, allocated and shared activities</td>
<td>Seemingly Unrelated Regression (SUR)</td>
<td>Males have stronger influences than females on joint household decisions; Variables affecting time allocation to allocated and shared household activities differ across males and females</td>
</tr>
<tr>
<td>Zhang &amp; Fujuwarra, 2006</td>
<td>38 elderly couples, 255 person days; Shimane, Japan</td>
<td>Time spent on in-home, independent, allocated and shared activities</td>
<td>SUR</td>
<td>Intra-household interactions significantly influence household time allocation; Husbands dominates wives in the household decision-making</td>
</tr>
<tr>
<td>Kato &amp; Matsumoto, 2009</td>
<td>89 (Tokyo) 303 (Toyama) nuclear households; Japan</td>
<td>Individual's time and expenditure consumed for leisure activity</td>
<td>Nonlinear Tobit model</td>
<td>Joint household leisure activities contribute significantly to household welfare; Individual leisure activities contribute differently to household welfare depending on other household members' roles/jobs</td>
</tr>
<tr>
<td>Wang &amp; Li, 2009</td>
<td>10,381 married couples; HongKong</td>
<td>Household decisions of hiring helpers and time allocation</td>
<td>Nonlinear Tobit model</td>
<td>Time allocation of males contributes more heavily to household utilities than females; Optimal helper-hiring time and optimal time allocation patterns depend on household income, no. of children, car ownership and type of housing</td>
</tr>
</tbody>
</table>

2.3.4 Activity generation and scheduling

A few studies in intra-household interactions investigate other aspects of activity - travel patterns, namely activity participation and activity scheduling. Both structural equations
modelling (SEM) and random utility approaches have been used to explore the role of household interactions in travel behaviour and activity participation.

Using the SEM approach, Golob and McNally (1997) and Schwanen et al. (2007) investigated between-spouse interactions in household out-of-home activity participation. These studies captured partner interactions by modelling their joint activities and postulating causal relationships between male’s and female’s activities. The difference between the two studies is that Golob and McNally (1997) studied household demand for all out-of-home activities (subsistence, maintenance, discretionary) and associated time spent travelling while Schwanen et al. (2007) focussed on the maintenance activity only. Both studies showed that the decision of participating in out-of-home activities of one partner significantly influenced that of the other partner. On the one hand, Golob and McNally (1997) using a sample of 1,292 couples in Portland, USA provided evidence of a statistically significant error covariance structure between male and female activities and travel, supporting the role of joint household activities and travel in household demand for activity participation. On the other hand, Schwanen et al. (2007), looking at the role of the household’s spatial setting and using a sample of 790 spouses in Amsterdam and Utrecht, The Netherlands, argued that the allocation of household tasks between partners was influenced by land use and accessibility factors although their effect appeared to be smaller than that of household socio-demographic characteristics and other activities scheduled on the same day. Similar results using the same dataset and modelling approach can be found in Ettema et al. (2007).

Using a random utility approach, Wen and Koppelman (2000) adopted an individual utility maximising approach to model the generation of maintenance stops, the allocation of household car and household members, and the formation of tours to perform these maintenance activities. The choices within each stage were estimated using a nested logit model due to available software and clear interpretation. Gliibe and Koppelman (2002) developed a time share model to describe a collective, as opposed to a collaborative, process of allocating individual’s daily time to joint and solo activities. The collective process implied the joint decision emerges as household members individually form preferences for joint participation, following a set of stable strategies, household needs and constraints (Gliibe and Koppelman, 2002). Adopting this same and common assumption in the household decision-making, Scott and Kanaroglou (2002) modelled the daily number of out-of-home non-work activity episodes, using trivariate ordered probit models. These studies explored intra-household interactions by examining independent and joint activity participation decisions of
households with two adults. The activity choices of individuals were found to be impacted on by household characteristics (the presence of children, life cycle, car deficiency, income), situational factors (flexible working hours, day of the week, season of the year) and travel-activity patterns of the other household members (Scott and Kanaroglou, 2002; Srinivasan and Bhat, 2005; Zhang, 2005; Srinivasan and Bhat, 2006). Scott and Kanaroglou (2002) also found that interactions between the household heads were significant and different across household types classified by the number of workers. More importantly, they found that for each household type, models with interactions predicted the number of solo and joint episodes undertaken more accurately than models without interactions. These empirical results suggest that intra-household interactions should be explicitly incorporated for a more realistic analysis of behavioural responses of households to changes in transport system, land use and socio-economic characteristics.

From the time use perspective, Srinivasan and Bhat (2006) developed a Multiple Discrete-Continuous Extreme Value (MDCEV) model, which opens a way to explore joint household activities and travel patterns across multiple dimensions when discrete choice models suffer from a combinatorial explosion. Their practical model investigates 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 determined 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 were represented using an error correlation structure. They found that activity pattern of the individual impacts on their partner’s discretionary activity patterns and the decision to pursue activities jointly, using a sample of 5,381 married couples in San Francisco, USA.

A general theme of the studies reviewed above is that the allocation of activities between household members was based on gender. Vovsha et al. (2004b), in contrast, analysed the allocation of maintenance activities across employment status of household members classified as full-time worker, part-time worker, student, non-worker, and children of preschool, pre-driving and driving ages. They found that household preferences in the allocation of maintenance activities were strongly linked to person type, time availability, daily activity pattern, and residential location. Srinivasan and Athuru (2005) were more concerned with the effect of heterogeneity on the allocation of activities among household members. They
developed a nested mixed logit model to examine the joint participation and the allocation of solo maintenance activities among household members. Their model relaxed several important assumptions regarding the error terms and was able to quantify the difference in terms of person allocation across households with different characteristics. However, Srinivasan and Athuru (2005) considered the joint activity participation as the final decision and did not identify the participants nor the party size when a joint activity was selected. The model results indicated that individual characteristics (household role, gender, employment status) and household life-cycle variables (presence of children, household income) play an important role in determining joint and solo activity participation in maintenance activities.

Joint household travel was investigated by Vovsha et al. (2003) who identified nine joint household tour types and classified them into three joint travel categories: fully joint tour for shared non-mandatory activities, synchronised mandatory activity tour, and escorting tour. Each joint travel category, reflecting different patterns of household travel arrangement, was modelled explicitly through a series of multinomial logit models: a joint tour frequency model, a travel party composition model, and a person participation model. Using data from Mid-Ohio in the USA, the descriptive analysis found that joint household travel accounted for almost half of the home-based motorised tours on weekdays. While the empirical model focused on the fully joint tour only, the influential attributes in arranging joint household travel were person type, household car ownership, household income, household size, and the time window availability after the scheduling of mandatory activities (Vovsha et al., 2003). This approach provides valuable insights into interpersonal dependencies in household travel arrangement, although it lacks a structural linkage between model components and relies upon simulation to ensure consistency between household members (Gliebe and Koppelman, 2005).

Intra-household interactions between adults and children were examined by Vovsha and Petersen (2005) who focused on school travel with or without drop-off/pick-up. Each school tour was divided into two half tours (home-school and school-home) with each having three options of travelling: ridesharing with a household driver, pure escorting by a household driver, and no escort. A nested logit model was applied at the entire tour level to choose potential household chauffeurs for each student in both directions. Using data from Atlanta in the USA, they found that chauffeur characteristics (gender, employment status, and age), children age, household car ownership, household income, and relative distances between home, school and workplace had a statistically significant influence on the decision of
choosing chauffeurs for school travel. Although this model was concerned with considering only car tours and treating separately the school tours of each child within the household, the model is capable of representing explicit interactions between adults and children in school travel, an important segment of intra-household interactions influencing mode choice for commuting purposes (work and education).

Adopting the method proposed by Vovsha and Petersen (2005), Yarlagadda and Srinivasan (2008a) examined school travel mode choices of students in single-parent and nuclear-family (couples with children) households using a sample of San Francisco Bay Area households. Their model explicitly identified the escorting person (mother, father or non-household member) and considered all possible travel modes to and from school using a wide array of explanatory variables. They found that a child’s mode choice to and from school was strongly linked to the parent’s employment status and flexibility at work, signalling the existence of intra-household interactions in household travel arrangements.

Intra-household interactions between parents and children was also investigated by McDonald (2008) who focused on active school travel (i.e., walking and cycling) of students aged 5 to 18 years in two parent households sampled from the US Nation Household Travel Survey. The study found that intra-household interactions in school travel was strongly moderated by the child’s age with younger students showing a heavier reliance on their mothers for school travel. As a result, separate binary logit models were estimated for younger students (aged 5 – 14) and older students (aged 15 – 18) to assess the differential impacts of mothers and fathers on children’s active school travel. She found that if the mother commuted to work in the morning, this reduced the probability of younger children walking or cycling to school by eight percent while the same commuting pattern had no effect on the active travel of older children. In contrast, the commuting patterns of fathers had less influence, consistent with earlier studies (Vovsha and Petersen, 2005; Yarlagadda and Srinivasan, 2008a).

Gupta and Vovsha (2013) examined the coordination of departure and arrival time choices for work tours between two workers in the same household. This type of interaction has received little attention in the literature. They investigated intra-household interactions based on the premise that workers jointly schedule their commuting tours to create overlaps of time windows for joint activities and travel not included in the work tours. Intra-household interactions in the scheduling of work tours are captured through synchronization effects, which they estimated using a hybrid discrete choice-duration model that operates in discrete
space with a 1-h temporal resolution. Their estimation results indicated a tendency of workers in multi-worker households to schedule work tours to create longer time window overlaps, signalling the coordination between workers in their choices of departure and arrival time. The coordination and synchronisation mechanisms were also found to be different across workers and households. These results suggest that activity scheduling is subject to intra-household interactions which should be modelled explicitly for a better understanding of travel behaviour and a more credible policy analysis.

Another avenue of research using a random utility maximisation framework incorporates intra-household interactions through classifying and modelling each household member’s daily activity pattern (DAP). Vovsha et al. (2004a) studied intra-household interactions through the coordination of DAPs between household members. They classified household members into seven types, ordered on a priority according to their occupation and age, and modelled each household member’s DAP sequentially. With this framework, lower priority household members were assumed to consider the choices of higher priority household members as a constraint in maximising their own utility. This approach only allows pair-wise interactions to be investigated although interpersonal linkages are incorporated explicitly. The results indicated that the linkage across activity patterns of household members were statistically significant, suggesting the importance of the entire household members for modelling each person’s DAP.

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 household head while modelling their joint choices simultaneously. Also, the PCCL model allows the impacts of contextual and situational factors on household interactions to be parameterised. However, the choice structure has to be constructed to satisfy joint decision constraints imposed on the decision makers acting in parallel. This enforcement means that substitution relationships between joint DAPs are pre-defined and the model cannot be used to explore various substitution structures, especially when all household members are considered. Another drawback of this approach is that the number of unique individual DAPs increases with the variation in travel pattern complexity, resulting in a large number of elemental alternatives in the choice system. Gliebe and Koppelman found that full-time workers and women with young children had a stronger influence on the household decision-making. They also reported that arrangements of joint household activities and shared rides were impacted by car availability, the total number
of children and workers in the household, the worker’s commuting distance and the separation
distance between workplaces.

Recognising the importance of the entire household in modelling each person’s individual
DAP, Bradley and Vovsha (2005) proposed a model for joint choice of DAPs, in which all
household members were considered acting as agents in the household decision-making. Pair-
wise and triple-wise interactions in the joint choice of DAPs were explicitly incorporated in
their model which simultaneously treated all possible combinations of individual DAPs for up
to five household members. The group-wise interactions were found to be statistically
significant, suggesting coordination among household members in scheduling their DAPs.
However, they used a loose definition of joint DAPs which did not necessarily mean joint
household activities nor shared rides but rather the individual’s choices of the same DAP
classified into mandatory (work, education), non-mandatory or at-home patterns. Moreover,
the model choice structure is complex and sensitive to household size and the number of basic
DAPs considered, to the extent that the technical management in estimation and application of
the model was an issue (Bradley and Vovsha, 2005).

In addition to these studies focusing on particular aspects of activity-based travel behaviour,
more comprehensive models in this research area have been developed using simulation
techniques. The simulations attempt to model group decision-making through specifying
behavioural mechanisms and introducing complexities which arise from interactions between
household members. Meister et al. (2005) took a genetic algorithm to generate household
activity-travel schedules based on household members’ activity calendars and the composition
of a household that was assumed to derive utility directly from joint participation in activities
and indirectly from the allocation of activities and modes of transport to household members.
Arentze and Timmermans (2009) introduced the concept of “need” to make various activities,
and the concept of the “potential” of activities to satisfy needs at both individual and
household levels for the process of interaction and Roorda et al. (2009) uses the idea of
“stress” (as discussed earlier). But these simulation models are effectively only an extension
of individual-level simulation of decision-making where household characteristics have been
incorporated mainly as explanatory variables in individual-level models. Moreover, “because
these simulation models used observed data, they lack behavioural mechanisms of how
individuals and households adjust their preferred schedules in time and space to cope with the
various types of constraints” (Timmermans, 2009, p.162).
The issue of consistency in scheduling joint activity and travel in space and time is examined by Liao et al. (2013) through the concept of multi-state supernetworks. From the viewpoint that travel is differentiated in terms of activity, vehicle and joint states, Liao et al. extended individual supernetworks to joint supernetworks to consider the joint travel dimension of individual activity-travel patterns. In this, the inter-dependencies of route and travel mode choices for joint travel between two persons are represented. Three different scenarios, corresponding to three specific joint travel patterns between two persons with one joint activity in their schedules have been examined, assuming disutility minimisation and cooperative decision-making. Three shortest path algorithms were developed to find the optimal solution for each of the three joint travel patterns. These solution algorithms add methodological value to ensure the consistency of multi-modal and multi-person travel, although the author noted that “substantial numerical experiments should be carried out to prove the efficiency of the proposed algorithm” (Liao et al., 2013, p. 824).

### 2.4 Heterogeneity in Group Decision-Making

Transport studies related to intra-household interaction usually assume that group decisions are context-independent. However, empirical research has shown that joint decisions do vary across households (Scott and Kanaroglou, 2002; Srinivasan and Athuru, 2005; Zhang et al., 2009). The household context (life cycle, the number of vehicle vs. the number of licence holders, working hours of the workers, the number of workers) and spatial setting may affect the strategy that a household adopts to organise travel for the whole household. In this regard, Scott and Kanaroglou (2002) found that interactions between household heads when making decisions concerning the number of joint and solo non-work activities, did vary across households with different number of workers. Specifically, non-worker and dual-worker households exhibited both collective (who does what) and opportunistic decision-making while interactions between the heads of single-worker households indicated significant gender roles. Similarly, Lee et al. (2007) found that household types, classified by the number of household heads and work status, were the main determinants of time allocation in trip chains. Intra-household interaction is also found to be an important aspect of time allocation for out-of-home subsistence, maintenance and discretionary activities within trip chains. In particular, households with time-flexible worker(s) tended to make less trip chains for the work trip (Lee et al., 2007). Furthermore, the presence of children was correlated with more time spent on household trip-chaining for all out-of-home activities. Srinivasan and Athuru (2005) reported a similar influence from the presence of children on the propensity to participate in out-of-
home maintenance activities of the household heads with significant differences in activity allocation across households with different income groups and number of cars.

Another important aspect of group decision-making is that heterogeneity can occur not only at the household level but also at the individual level. There is little foundation for viewing households as homogenous decision-making units (Timmermans, 2009). Different household members may have different preferences or relative influences for the same decision target (Zhang et al., 2009). This gives rise to conflicts between household members and forces them to negotiate with each other using strategies such as bargaining, compromising, and persuasion to reach a consensus among household members (Davis, 1976). Timmermans (2009) argued that as individual weights do not appear to be the same across choice situations but depend on context, preference intensity and other situational variables, identifying context-dependent relations is more productive than adding increasingly more variables to account for heterogeneity. This highlights that the assumption of individual relative influences in household decisions is better than assuming a homogeneous household decision-making unit.
Previous studies of group decision-making in transport research, especially in activity-based travel behaviour, have identified some important elements directly contributing to interactions within a household. Table 2.3 shows the context and results from these studies reported in the literature. Table 2.3 suggests that the role of land use characteristics and situational factors such as the nature of the choice task and the perceived risks of, for example, being late if public transport modes are used, remain unexplored in the literature looking at interactions.

Table 2.3 Summary of influential factors in intra-household interactions

<table>
<thead>
<tr>
<th>Author</th>
<th>Context of study</th>
<th>Factors determine members’ weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abraham &amp; Hunt, 1997</td>
<td>Transport and land use integration</td>
<td>Gender</td>
</tr>
<tr>
<td>Gliebe &amp; Koppelman, 2002; 2005</td>
<td>Joint activity participation</td>
<td>Employment status, The presence of young children</td>
</tr>
<tr>
<td>Zhang &amp; Fujiwara, 2009</td>
<td>Residential relocation choice</td>
<td>Gender, Age, Decision maker of household matters</td>
</tr>
<tr>
<td>Zhang et al., 2009</td>
<td>Car ownership</td>
<td>Age, Employment status, Car main user</td>
</tr>
<tr>
<td>Zhang et al., 2002; 2005</td>
<td>Time use</td>
<td>Number of workers, Social status, Age of the oldest household member, Number of vehicles, Travel time</td>
</tr>
</tbody>
</table>

*Household members’ weights were indirectly derived rather than directly estimated.*

2.5 Intra-Household Interactions: Methodological Approaches

Section 2.3 and Section 2.4 have reviewed the empirical findings from studies focusing on joint household decisions and intra-household interactions. The literature suggests that household interactions appear to be a relevant factor to decision-making. With respect to methodology, research has addressed the complexity of interpersonal interactions and group decisions in a variety of ways. This section describes and critiques the various methodological approaches adopted to study interpersonal interactions and group decision-making with a particular focus on data and modelling techniques.

2.5.1 Survey techniques and data requirements

Empirical studies devoted to interpersonal interactions and group decisions have used primary data from study-specific surveys or secondary data mainly from travel diaries. The former is collected by stated preference (SP) survey techniques using Household Activity Travel Simulator (HATS), Hierarchical Information Integration (HII), and Interactive Agency Choice
Experiments (IACEs). These techniques are briefly discussed below including an example application of each technique to study intra-household interactions.

The interview-based HATS technique, developed by Jones (1979), considers the household rather than the individual as the major decision-making unit. The survey procedure typically includes three steps. Prior to the main interview, participating household members are asked to record their activity-travel patterns for a certain number of days from which a typical day is chosen and visually represented to start the main HATS interview. Based on this visual representation, the interviewer initiates a discussion of the reasons for the observed daily activity-travel patterns and explores the temporal, spatial, budgetary and interpersonal constraints operating within the household. The interviewer then specifies a change and asks household members to consider the effect of the change, modify their activity-travel patterns which may lead to linked changes to patterns of other household members. This procedure is iterative until a consensus among household members is obtained. After the interview, modifications to household activity-travel patterns brought about by the change considered are recorded to provide the analyst with ‘before’ and simulated ‘after’ datasets.

The group interview format of the HATS technique helps to gain insights into the household decision-making process and interpersonal linkages. This technique is particularly useful for use with larger households with complex activity-travel patterns, greater constraints and linkages. However, it has several limitations when used on its own. First, due to the logistic challenge of respondent recruitment, survey preparation and administration, the sample size is generally small and may not be representative of the population of interest. Second, in-depth interviews do not allow the effect of intra-household interactions and individual weights on household activity-travel patterns to be quantified. In an example application of the HATS technique using a small sample size of 34 households, Jones (1978) found that a 30-minute change to school hours affected the activity patterns of not only students attending school but the remaining household members.

The HII approach, originally proposed by Louviere (1984), assumes that individuals use multistage decision strategies to process information in complex decision-making tasks. In particular, individuals are assumed to group a large number of potentially influential attributes into a smaller set of decision constructs, evaluate each of the decision constructs separately, and integrate their evaluations into overall preferences for the decision alternatives. Timmermans et al. (1992) extended the original HII approach to represent the group decision-
making with a two-stage experiment. The first stage was similar to the original HII approach and required group members to evaluate independently each decision construct. The second stage involved a group task where the influence of each group member on the group preference or choice was measured with a bridging experiment which varied group member preferences for each decision construct. Molin et al. (1999) later extended this conventional HII approach, combining attributes that define a particular decision construct and the group member preferences for the remaining decision constructs into one integrated experiment. This approach, referred to as integrated HII, removes the bridging experiment and requires only group tasks. Molin et al. (2002) found that for residential preferences, the group-based integrated HII model was more reliable and had higher validity than the group-based conventional HII model.

The IACEs approach, developed by Hensher (Hensher and Chow, 1999; Brewer and Hensher, 2000) involves sequential interactive experiments in which group members have the opportunity to amend their stated preferences based on the preferences of other group members. The observed process of feedback and preference revision enables the analyst to quantify the effect of interactions between group members (called agents) on the formation of preferences and the final choice outcome which can be either agreement or non-agreement. The drivers of influence on agreement and non-agreement can be identified, as can the relative influence and power of each agent in the group decision-making.

Despite the behavioural appeal of the IACEs approach, applications to study intra-household interactions have been limited by the cost of collecting data. The iterative process of IACEs, until either consensus or impasse is reached, results in more time and effort per choice set than standard choice experiments. Furthermore, model estimation and experimental design increases in complexity as more agents are included. In an application of the IACEs technique to study car purchase decisions, Hensher et al. (2008) found that individual preferences for car purchase were revised through a process of feedback, review and revision to establish the joint preferences.

Another approach to collecting data for analysing intra-household interactions is to use secondary data. Household travel surveys collect substantial information at the individual level and the challenge in using these data is how to identify joint travel. The literature summarised in Table 2.4 has shown how joint household activity participation and shared rides can be identified by using matching criteria. Joint household travel/activity episodes are
identified by matching each household member’s daily trip records, comparing reported household identifiers, the number of household members involved, departure and arrival times, trip origins and destinations, and/or travel purposes. Table 2.4 summarises the different sets of matching criteria in the literature to identify joint household activities and travel. It should be noted that the percentages of joint household activities and travel (shown in the last column) are not comparable across studies due to different units of analysis and number of household members considered (the second column).

Table 2.4 Overview of studies related to the identification of joint household activity – travel

<table>
<thead>
<tr>
<th>Study</th>
<th>Sample/Location/ No. of household members included</th>
<th>Matching criteria</th>
<th>Share of joint activity/travel †</th>
</tr>
</thead>
</table>
| Singhi (2001)          | 139 households 317 persons over 6 weeks 52,273 household trips/ Halle and Karsruhe, Germany/ Up to 5 members     | - Same study code  
- Same city code  
- Same household ID  
- Same day  
- Same main mode of travel  
- 5 mins difference in departure & arrival times | 22% of trips are joint.  
Of which:  
17.4% are by 2 persons;  
3.5% are by 3 persons;  
1.1% are by 4 persons;  
0.1% are by 5 persons. |
| Vovsha et al. (2003)   | 10,800 households 34,940 tours (New York) & 5,555 households 18,189 tours (Mid-Ohio) USA/ Up to 10 members | - Same household ID  
- Same day  
- Same departure/arrival time for outbound leg of main tour  
- 5 mins difference in other arrival & departure times  
- Same destination (for pick-up & drop-off tours only) | 37.7% (New York) & 46.2% (Mid-Ohio) of motorised home-based tours are joint;  
75% to 80% of joint car tours are made by intra-household travel parties. |
| Gliebe & Koppelman (2005) | 26,492 weekday person records/ Washington, USA/ 2 adults | - Same household ID  
- Same origin & destination  
- Same activity type  
- Same travel mode | 29% of individual daily records involve a joint out-of-home activity episode and/or a shared ride. |
| Kang & Scott (2008)    | 240 households 474 adults over one week 28,680 person activities/ Toronto, Canada/ 2 adults | - Same activity type  
- Overlap in activity time  
- Same aggregated mode  
- 10 mins difference in departure & arrival times | 44.5% of episodes are joint with 10.1% being out-of-home;  
16.1% of trips are joint. |

†Percentages differ substantially across studies which use different units of analysis denoted in italic and defined in the corresponding study as follows:

- Trip: any movement from one place to another, including change mode and return home
- Tour: a sequence of trips starting and ending at the individual’s home
- Daily record: an individual’s full-day activity-travel pattern, combining all tours and activities undertaken
- Episode: a period of activity participation at a single location for a single purpose

Theoretically, household members would report the same trip details including departure and arrival times, origin and destination for a joint household trip. In practice, a joint household trip might be reported inconsistently by the different participants in the survey because most
data are captured for one person at a time and not one trip at a time. Therefore, using a set of restrictive rules (i.e., same mode, same timing, same location, and same travel party size) for identifying joint trips/activity episodes is likely to under-identify joint household travel. Kang and Scott (2011) suggested that a flexibly defined set of matching criteria (more aggregated travel modes, and proximate timing as opposed to same timing) may improve the identification. However, because identifying which person was involved in the activity was not available in their dataset, the extent to which different matching criteria may under-identify or over-identify joint household travel and activities could not be ascertained.

2.5.2 Modelling techniques

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 Fujii et al. (1999) and Zhang et al. (2005). The second approach is based on discrete choice models and time share models such as Scott and Karanoglu (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 such as Srinivasan and Bhat (2006). Finally, the fourth approach is based on generic algorithm, implemented by micro-simulation such as Meister et al (2005). This section provides an overview of these approaches as the more detailed description of the ways in which each technique incorporates intra-household interactions and example applications of each technique are discussed in Section 2.3 above.

From the household decision-making perspective, in each of the methodologies mentioned 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), Schwanen et al. (2008b). The second class explicitly incorporates group decisions into household travel behaviour models using different types of group utility functions, which include works of Timmermans et al. (1992), Abraham and Hunt (1997), Gliebe and Koppelman (Gliebe and Koppelman, 2005; 2005), Meister et al. (2005), Miller et al. (2005), Zhang et al.(2009), Kato and Matsumoto (2010). The main difference between the two modelling classes is the incorporation of household interactions and group decision rules in the second class.
The individual-based approach, used in most activity-based travel demand modelling systems, classifies intra-household interactions into several components and models them sequentially. 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 have been considered in the literature. These are the coordination of household members’ daily activity-travel patterns (DAP), serving household members with restricted mobility by providing drop-offs and pick-ups, engagement in joint household activities, sharing household maintenance responsibilities, and allocation of household cars (Srinivasan and Bhat, 2005). The main drawback to this approach is that it is based on individual behaviour and therefore does not allow different household members to play different roles in the joint household decisions. Nonetheless, with an appropriate model specification, the individual-based modelling approach can add valuable insights into intra-household interactions.

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). Different assumptions on the group and individual behaviour underlie the use of these group utility functions with initial evidence of household car ownership suggesting the existence of heterogeneity in group decision-making mechanisms (Zhang et al., 2009; Zhang and Fujiwara, 2006). Generally, the group decision modelling approach defines the household as the decision making unit with different household members playing different roles and collectively determining behaviour. The group-based approach typically faces the challenge of representing choices of multiple-person households due to the combinatorial explosion of potential alternatives. Consequently, the 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 the daily activity-travel pattern and travel mode, the agents have been limited to the household heads so as to prevent over-complex structures arising where specification constraints are required to overcome the estimation and management issues.
2.6 Research Gaps and Research Hypotheses

Travel mode choices have received the most intensive study in the existing literature. These studies have found that fares, quality of service, household car ownership, household income, and land use patterns are important to mode choice decisions. In addition, socio-economic characteristics appear to have a stronger effect on travel behaviour than land use patterns do. However, most of the existing evidence is based on individual analysis which considers travel demand generated at the individual level using household characteristics as explanatory variables, without direct regard to intra-household interactions.

Intra-household interactions imply the travel decisions of a household member are contingent on the travel decisions of other household members. The existence of intra-household interactions giving rise to joint activity participation and interdependencies in travel decisions has long been acknowledged, yet empirical studies of intra-household interactions have remained rather limited. The limited evidence is partly due to the absence of information on participating household members in activity based travel surveys, the difficulty of extracting such information where it exists, detecting and correcting data inconsistencies reported by participating household members from travel diary surveys and difficulties in defining and analysing all possible joint household travel patterns. This chapter has identified four main approaches (i.e., multiple continuous choice models, discrete choice models, discrete-continuous choice models, and simulation) used in the literature to empirically accommodate intra-household interactions, and has reviewed the empirical findings and data requirements of selected studies using those approaches. The following section identifies research gaps which lead to the generation of research hypotheses specified in the next section.

2.6.1 Research gaps

Previous studies confirm that intra-household interactions exist, 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 explicitly identified individual relative influences (e.g., Gliebe and Koppelman, 2005; Zhang et al., 2009). However, 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. Data limitations have constrained the extent to which previous studies have been able to consider interactions amongst all household members in daily activity-travel arrangements. This is the first gap in the literature.
In fact, most of these studies use data from activity-travel surveys that do not often collect activity-travel diaries of all household members with children under 15 years old being ignored and with limited information on travel/activity companion (Vovsha et al., 2003; Srinivasan and Bhat, 2008). As a result, different sets of matching criteria (see Table 2.4) have been used to identify joint household activities and travel with uncertainty about under- and over-identification being remained. In addition, methodological difficulties still represent a major challenge to study interactions amongst all household members as most previously proposed approaches are for two-person households which cannot be generalised to handle the entire household.

Another gap in the literature on joint household travel relates to the underpinning theory and modelling approach. More theoretical and empirical analyses of intra-household interactions are required to link various activity-travel decisions while taking account of interpersonal dependencies. Also, 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 arrangements and mode choices given that activities have already been generated. The complex nature of intra-household interactions in these repeated choice situations has led a number of previous studies to undertake simulation as a way of avoiding challenges associated with analytical tractability (Miller et al., 2005; Roorda et al., 2006). Theoretical underpinning of these simulation models needs further consideration. For example, modelling intra-household ridesharing conditioned on mode choice decisions fails to recognise that joint household travel may predetermine the travel mode. In this regards, analytical approaches such as those proposed by Vovsha and Petersen (2005) and adapted by Yarlagadda and Srinivasan (2008a) may have more to offer, although intra-household interactions have been simplified by focusing on school travel and assuming serve household passenger being allocated directly to the passenger’s activity location (as opposed to, for example, a train station for onward travel).

A third research gap relates to the practical and application purposes of travel demand models. Research has focused on joint household activity-travel mostly for weekday travel and much less for weekend travel. As joint activity participation and joint travel arrangements are found to be greater on weekends than on weekdays (Lockwood et al., 2005; Srinivasan and Bhat, 2008), modelling weekend travel with intra-household interactions has emerged as an important direction for further research. Finally, travel decisions are made under certain social, temporal and spatial constraints. Thus, household interactions are expected to be
context-dependent in the sense that household interactions may depend on household context, environmental setting, and choice situation. This requires a more micro-level approach to investigate the effect of land use factors and time synchronisation on intra-household interactions. The use of a micro-approach for an investigation into the relationship between land use and travel mode use will provide evidence to support transport policies and planning practices.

2.6.2 Research questions and hypotheses

Driven by the research gaps, four elements influencing household travel mode choices are studied in this research: household interaction, household context, choice situation, and land use factors measured at the micro-level. This study integrates these four elements into a modelling framework thus addressing the deficiencies of existing studies which have been partly due to data limitations and partly due to methodological difficulties. The study poses the overarching question that if household interactions are a relevant factor in decision-making, what difference do these interactions make to the implications for transport policy and what are the benefits of studying intra-household interactions? More specifically, this study examines whether intra-household interactions giving rise to joint household activity participation and shared ride arrangements are prevalent in regional travel demand and important to the formulation of transport policies and planning practices for sustainable transport choices. In addition, this study considers how joint household travel arrangements influence individual travel mode choices and what if intra-household interactions are not taken into account in analysing transport policies. The research also examines the motivation for and constraints on joint household travel arrangements and whether these are different across weekdays and weekends. These principal questions are addressed through the following hypotheses:

Hypothesis 1. Household interactions underlie observed individual travel mode choice and are affected by:
- Household context (the number of vehicles vs. licence holders, household size, household type).
- Choice situation (travel purpose, time schedule synchronisation, travel party composition, work hours) for a given residential location.
- Social and mobility constraints (e.g., very young children neither stay home alone nor travel independently).
Hypothesis 2. Travel mode choices of different joint household travel arrangements are influenced by land use characteristics measured at a micro-level such as:

- Proximity to public transport (Origin and Destination).
- Degree of mixed land use (Origin and Destination).
- Activity density (Origin and Destination).
- Aspects of network design and layout (e.g., walk-ability at Origin and Destination).

Hypothesis 3. Weekend travel is significantly different from weekday travel in terms of joint household travel arrangements and shared activities.

Hypothesis 4. Joint household travel analysis identifies different modal shifts for policy outcomes, as compared to individual travel analysis.

The first hypothesis aims to test the relevance of intra-household interactions in travel mode choice, in contrast to the literature which has tended to focus on intra-household interactions in the generation of household activity. This study also explores the motivation for joint household travel and the circumstances under which it occurs. This is important for developing policy, for example, in 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 cars.

The second hypothesis aims to explore the impact of land use characteristics measured at a micro-level on travel mode choice. As discussed in Section 2.1, the effect of land use factors on travel mode choice has been considered but mostly at a macro-level and mainly from an individual decision perspective. From a joint household decision perspective, this study aims to provide a more micro-level approach to the effect of land use factors on travel mode choices and joint household travel arrangements. Sustainable transport choices presented by policy makers and transport planners are typically built on micro-level evidence. Testing this hypothesis will provide evidence on the effects of land use factors measured at the micro-level so as to identify those measures most likely to support policy change for sustainable transport choices. Decisions regarding residential location choice are treated as given in this
study because transport facilities and their impact on travel behaviour are only one out of many factors influencing location choices (Timmermans et al., 1992; Borgers and Timmermans, 1993; Zhang and Fujiwara, 2009).

The third hypothesis aims to compare joint activity-travel patterns of weekdays and weekends. Most previous studies on joint household travel arrangements and joint activity participation focus on weekday patterns and, where comparison with weekday patterns has 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). Testing this hypothesis not only fills this gap but also suggests effective transport management measures which tend to be different between weekdays and weekends for the same purpose of reducing traffic congestion and encouraging sustainable travel choices.

The fourth hypothesis aims to provide empirical evidence of the importance of intra-household interactions to transport policy analysis and travel demand forecasting. It is practically relevant to understand how sizable under- or over-estimation of modal shift would be if joint household travel arrangements are not taken into consideration. This is because the difference has policy implications, in particular an assessment of policies for increasing public transport use by improving the level of public transport services or implementing HOV lanes.

These four hypotheses are tested with the empirical data and modelling approaches described in subsequent chapters. Chapter 3 describes the data sources and outlines the modelling approaches. Chapter 4 presents steps taken to transform the original data into that used for testing these hypotheses. Descriptive analyses are provided in Chapter 5 which partially addresses the first two hypotheses. Chapter 6 develops empirical models to fully consider the hypotheses outlined above.
CHAPTER 3. DATA SOURCES AND METHODOLOGY

Chapter 2 has discussed the research questions of this study and has reviewed a variety of methods used in the literature to investigate intra-household interactions. This chapter describes the data sources and presents the analytical concepts and models used to address these research questions. The chapter first describes the Sydney Greater Metropolitan Area, the study area of the Sydney Household Travel Survey where the data are collected for this research. General geographical and demographic characteristics of the Sydney Greater Metropolitan Area and its transport network are provided. This is followed by a description of data sources and a representation of intra-household interactions in household travel arrangements. Individual-based and group-based modelling approaches to analysing joint household activities and travel arrangements are then presented. The chapter ends with an evaluation of modelling approaches that can be used to study the influence of joint household travel arrangements on individual’s mode choices.

3.1 The Sydney Greater Metropolitan Area and Its Transport System

The Sydney Greater Metropolitan Area (GMA) is the study area of the Sydney Household Travel Survey (HTS) from which the main data of this research are constructed. Figure 3.1 shows the geographical coverage of the Sydney HTS which includes Sydney Statistical Division (Sydney SD), Newcastle Statistical Subdivision (Newcastle SSD), and Illawarra Statistical Division (Illawarra SD). Table 3.1 shows the basic geographical and demographic characteristics of the Sydney GMA. In 2010, the population of the Sydney GMA was 5.5 million people with 82% of the population residing in Sydney SD. The average population density across the Sydney GMA was 277 persons/km². Sydney SD was the densest region with 377 persons/km² equal to all that for Australian capital cities combined (ABS, 2012). Newcastle SSD is the second highest population within the Sydney GMA but the population density is much lower compared to Sydney SD. Illawarra SD had the smallest population and the lowest density in the Sydney GMA. Most of Illawarra’s and Newcastle’s population is concentrated along the coastal and hinterland areas where the average population increase in the ten years to June 2010 in is faster than that in inland areas (ABS, 2012). While the total area of Newcastle SSD and Illawarra SD is comparable to that of Sydney SD, the population is much higher in Sydney SD. Thus, the key demographic characteristics of the Sydney GMA are mostly driven by Sydney SD.
Table 3.1 Geographical and demographic features of the Sydney HTS study area, as at 2010

<table>
<thead>
<tr>
<th></th>
<th>Sydney SD</th>
<th>Newcastle SSD</th>
<th>Illawarra SD</th>
<th>Sydney GMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population ('000s)</td>
<td>4,575</td>
<td>547</td>
<td>436</td>
<td>5,558</td>
</tr>
<tr>
<td>Population density (persons/km²)</td>
<td>377</td>
<td>135</td>
<td>53</td>
<td>227</td>
</tr>
<tr>
<td>Population growth 2010-2011</td>
<td>1.3%</td>
<td>1.5%</td>
<td>1.0%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Households ('000s)</td>
<td>1,691</td>
<td>212</td>
<td>168</td>
<td>2,070</td>
</tr>
<tr>
<td>Average household size</td>
<td>2.7</td>
<td>2.6</td>
<td>2.6</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Data sources: National regional profile 2006-10 and Regional population growth, Australia, 2010-11 (ABS, 2011; 2012)

Figure 3.1 Sydney Greater Metropolitan Area (GMA)

In the year 2010-2011, Sydney SD had the annual population growth rate of 1.3% and reached 4.6 million people, remaining the largest capital city population in Australia (ABS, 2012). Of the three regions in the Sydney GMA, Newcastle SSD experienced the largest increase in population (up 1.5%) and Illawarra SD the lowest (up 1.0%). In 2010, Sydney GMA was home to about 2.1 million households with the average household size of 2.7 persons. Along with population growth, a decreasing trend in household size leads to the need of 700,000 additional dwellings between 2006 and 2036 (NSW, 2010a). The change in demographics inevitably results in decentralisation which in turn imposes greater challenges in providing sustainable transport services for Sydneysiders.

Table 3.2 provides key transport indicators for the three regions covered by the Sydney HTS. On an average weekday in 2010, residents of the Sydney GMA generated over 20 million trips with Illawarra and Newcastle residents making more trips than Sydney residents (BTS, 2012c). Average household vehicle ownership in Sydney SD was also lower than that of Newcastle SSD and Illawarra SD. Across the Sydney GMA, the private vehicle is the main travel mode with car driver and car passenger modes together making up over two-thirds of the modal share on an average weekday, followed by walk only (i.e., walk to/from an activity site as opposed to walk to/from a public transport node). Bus and train together account for about 10% of trips and the use of these modes is substantial higher in Sydney SD than in Newcastle SSD and Illawarra SD regions. This is due to the nature of the public transport network in Sydney and is discussed further below.

Table 3.2 Key transport indicators of the Sydney GMA, average weekday 2010

<table>
<thead>
<tr>
<th></th>
<th>Sydney SD</th>
<th>Newcastle SSD</th>
<th>Illawarra SD</th>
<th>Sydney GMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of trips</td>
<td>16,335</td>
<td>2,060</td>
<td>1,698</td>
<td>20,197</td>
</tr>
<tr>
<td>Trips per capita</td>
<td>3.6</td>
<td>3.8</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Household vehicle ownership</td>
<td>1.5</td>
<td>1.7</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Modal share, average weekday</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car as driver</td>
<td>47%</td>
<td>59%</td>
<td>54%</td>
<td>49%</td>
</tr>
<tr>
<td>Car as passenger</td>
<td>21%</td>
<td>23%</td>
<td>24%</td>
<td>22%</td>
</tr>
<tr>
<td>Bus</td>
<td>6%</td>
<td>3%</td>
<td>3%</td>
<td>5%</td>
</tr>
<tr>
<td>Train</td>
<td>5%</td>
<td>1%</td>
<td>1%</td>
<td>5%</td>
</tr>
<tr>
<td>Walk only</td>
<td>18%</td>
<td>12%</td>
<td>15%</td>
<td>17%</td>
</tr>
<tr>
<td>Others</td>
<td>2%</td>
<td>2%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Data source: TransFigure: Travel in Sydney, Newcastle and Illawarra (BTS, 2012c).
Sydney’s public transport system is made up of a network of buses, trains, ferries, taxis, and light rail with bus and train forming the major part of the public transport network. Passenger train services in Sydney include 17 lines and are operated by CityRail. Sydney’s train network is radial and extends from the Central Business District (CBD) to cover an extensive area as can be seen in Figure 3.2. With 308 stations spread over 2,242 km of track, the CityRail network is one of the world’s most complex systems which served approximately 820,000 passengers per day in 2011 (BTS, 2012b; NSW, 2013a). The radial nature of the train network lends itself as an important mode for long distance travel and for commuting purposes with about 50% of all Sydney train use being to and from work (BTS, 2003; 2013a). The majority of local travel demand is served by other modes of the public transport system.
Figure 3.2 Train network in Sydney GMA, as of 2012

Data sources: Developed from GIS layers.
Figure 3.3 Bus network in Sydney GMA, as of 2012

Data sources: Developed from GIS layers.
Figure 3.4 Bus contract regions in Sydney GMA, as of 2012

Data sources: Developed from GIS layers.

The bus network including local and inter-suburban bus services covers most areas of the Sydney GMA as shown in Figure 3.3. Local bus services cater for local travel demand and function as a feeder mode for train and inter-suburban bus services for connections to the Sydney CBD or other parts of the city. In all three regions, bus services are provided by operators contracted to the NSW government. Over the period covered by this research, bus
services in Sydney SD are divided into 15 metropolitan bus contract regions (MBCR) and one outer metropolitan bus contract region (OMBCR) in the far west of Sydney (see Figure 3.4). The government-owned operator State Transit Authority (STA) provides services in the four inner areas of Sydney (MBCR 6 to 9) and private operators provide services in the remaining 11 MBCR (Mulley and Ho, 2012 provide a more detailed review of the network planning and bus performance in these MBCR). Newcastle SSD is divided into 7 OMBCR and Illawarra SD two. Bus services in all but one of these OMBCR are provided by privately-owned operators. The exception is the OMBCR 5 in Newcastle which is operated by the STA Newcastle. All operators are paid a per km rate, and all fare revenue is retained by the government. The bus network offers reasonably high levels of service in the 4 inner areas of Sydney but most bus routes, which provide the main form of public transport in outer metropolitan areas, run less frequently especially on weekends and in off-peak hours.

The Sydney ferry network provides services on Sydney Harbour and the Parramatta River with the anchor point of all routes being Circular Quay located in the CBD (see Figure 3.5). Ferry services in NSW are operated by both government-owned and privately-owned operators. During the period covered in this study, ferry services in Sydney are operated by Sydney Ferries, an agency of the NSW Government. In July 2012, Sydney Ferries was franchised to private operators under the name of Harbour City Ferries (NSW, 2013c). Ferry services in Newcastle are operated by the STA under the name of Stockton Ferries. There are also a number of privately-owned ferry companies contracted to the NSW Government to provide services throughout NSW but these services are mainly for leisure purposes except for the Manly route with several changes to the operators (NSW, 2013c). Manly ferry services were initially operated by Sydney Ferries. The Sydney Ferries services on this route were discontinued at the end of 2008 and were replaced with Manly Fast Ferries, a privately-owned operator. In April 2010, Manly Fast Ferry contract had been replaced by another private operator, Sydney Fast Ferries and the two operators are now competing each other (Phillips, 2009; Murphy, 2010).
Figure 3.5 Sydney ferries network, as of 2012

The Sydney Ferries network with 8 routes connecting 39 destinations and spanning about 37 km of waterway forms the majority of the ferry services in the Sydney GMA. The ferry network served about 40,000 passengers per day in 2011 which translates to 0.2% of total trips (BTS, 2013a; b). Despite the small share of total trips made by ferry, this mode plays a unique role in moving people as without these ferry services, about 4,000 weekday commuter trips would have to shift to alternative modes of travel to access the CBD via the Sydney Harbour Bridge bottleneck (BTS, 2003). Ferry services are also important for leisure purposes and these account for 37% of total ferry trips on an average weekday and probably higher on weekends, especially on Sundays when Sydneysiders and visitors may take advantage of the popular $2.50 Family Funday Sunday tickets that offer heavy discounts for family groups (NSW, 2012; BTS, 2013a).

Finally, taxi and light rail services add to complete the picture of public transport services in the Sydney GMA. Taxi trips accounted for 0.6% of total trips on an average weekday in 2010 and are typically short in distance due to their relative high fares (BTS, 2013b). The light rail with only one route shares a very minor proportion of total travel demand. The Sydney light rail links the hub of Central Station and Sydney’s Inner Western Suburbs via Chinatown, Darling Harbour, the Star Casino, and Fish Market. With these popular destinations, light rail users are mainly tourists and commuters. The light rail does not run to any specific timetable but every 10 to 15 minutes during daytime and every 30 minutes overnight. Daytime and overnight services are different between weekdays and weekends with daytime services on weekends starting at 8 am and ending at midnight, compared to 6 am to 11 pm on weekdays. The light rail is currently being extended and the new service is planned to begin operating in early 2014. This 5.6 km extension started in November 2012 and will connect to the existing light rail service at Lilyfield, running through the Inner West to Dulwich Hill and will include 9 new stations (see Figure 3.6).
The public transport network in the Sydney GMA has a fully integrated ticketing system which was introduced via MyZone multi-modal tickets in April 2010 (NSW, 2011). MyZone are multi-modal tickets that provide unlimited travel on all trains, ferries, light rail, government and private buses in one of three zones for the period covered by the tickets. MyZone tickets are available for daily, weekly, monthly, quarterly and yearly. Apart from these multi-modal tickets, other ticket options including Mytrain, Mybus, Myferry are available for public transport users of a specific mode. Mytrain offers options in five distance based fare bands and Myferry two, both with discounts for longer term passes. Mybus provides three distance based fare bands with about a 20% discount for Travelten tickets, compared to ten single tickets. Bus users can also buy a ticket on board except for prepaid buses (Metrobuses) and buses in the CBD on weekdays between 7:00 am and 7:00 pm. Before the introduction of MyZone fare tickets in April 2010, the integration in tickets for public
transport users was available only via DayPass or DayTripper tickets but these are expensive with the cost of full day travel for non-concession holders being A$16 in 2007/08, A$16.50 in 2008/09 and A$17.60 in 2009/10 (IPART, 2008). The lack of integration in ticket for the most part of the period covered by this study means that bus users were penalised by requiring an additional ticket for every transfer made.

The description of the case study presented above has highlighted the key geographical, socio-demographic characteristics, transport indicators, and aspects of the public transport networks of the Sydney GMA. Like other metropolitan areas, Sydney faces the challenges of increasing demand for transport, dwellings and jobs because of a growing population and the population’s expectations for better accessibility. Planning strategies adopted by the NSW government in response to these challenges are to make jobs and dwellings available in the right places to reduce travel and for job locations to be supported by public transport (NSW, 2010a). The plan sets a target to deliver 70% of new homes within existing suburbs, allowing 30% of development to occur in new areas (NSW, 2010b). The Sydney CBD continues to be the core of businesses and activities with suburban areas being connected to the CBD by the radial train network. Outer areas are supported by buses to access the CBD and local business centres where train services are not available. The spatial configuration of urban form and public transport system of Sydney and its population trends make it a typical metropolitan city and thus can provide evidence that may be transferable to other similar areas. Indeed, Sydney’s configuration of urban form and public transport network is commonly seen in most Australian capital cities (Currie and Delbosc, 2011; Mees and Dodson, 2011). Thus, an investigation of the connections between land use patterns and travel demand in Sydney may provide practical implications for public transport planning and policy practice to other cities with similar land use and travel patterns. As this study examines the role of joint household travel and land use patterns in influencing travel mode choices, the availability of rich survey data for the entire household adds another important reason for the choice of Sydney as a case study. The next section describes the data sources available for the Sydney GMA.

3.2 Data Sources

The data used in this study includes the Sydney GMA Household Travel Survey, travel system performance data from the Sydney Strategic Travel Model (STM), and land use data from multiple sources. These sources are described below.
3.2.1 Travel data: Sydney Household Travel Survey

The Sydney HTS was first conducted in 1997/98 by the Bureau of Transport Statistics (BTS) and has been running continuously since then. To date, the dataset includes fourteen consecutive waves and is the longest running continuous household travel survey in Australia (BTS, 2012a). The surveys are carried out every day from July to June of each financial year. About 5,000 households are randomly selected and approached each year, of which approximately 3,500 households with about 8,500 people participate (BTS, 2011a). The average yearly response rates from 1997 onward have been always above 62% (Merom et al., 2010; BTS, 2011a). Each wave includes a survey of household characteristics, person characteristics and a 24-h travel diary for each participant, including children of all ages. 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 is designed to increase accuracy. Within the survey, a question is asked about how many people travel in each car trip and so for the car mode only, the travel party size is available. The Sydney HTS data are organised into a large database with household, person, trip, and vehicle records that can be linked (BTS, 2012a). This section describes the data files used in this research.

The dataset constructed for this research is a pool of the three latest available waves at the time of writing this chapter (2007/08, 2008/09 and 2009/10) for households in the Sydney SD. Pooling the three waves ensures sufficient observations of infrequently-observed travel patterns while it is the finer geographical aggregation (i.e., smaller size of travel zones) which leads to the choice of Sydney SD. The finer travel zones are important for more refined spatial analysis because a number of land use variables used in the empirical models are only available at the travel zone level. Using Sydney SD means that when all households in a travel zone are given some average characteristics in terms of their spatial setting, this is at a relatively fine level. Focusing on Sydney SD also benefits from its central location, with an extensive coverage of the public transport network and a lower level of external travel where network data (discussed in Section 3.2.2 below) are not available. The raw dataset includes 7,286 households with 17,487 persons. Four types of data files were used: household, vehicle, person and travel diary.

The household data files contain records for approximately 2,400 households in Sydney SD per annual wave. Data fields include: household income, household size, the number of people aged 15 or over in the household, the number of children aged 0 to 14 in the household, the number of vehicles usually used by the household, household lifecycle, the
indicator of partly or fully responding household, the number of licence holders in the household, dwelling ownership status and dwelling structure type, date of travel, local government area (LGA) and travel zone (TZ) of the household, and variables indicating the number of trips made by different modes of travel including car driver, car passenger, train, bus, walk, and others (including ferry, light rail, bicycle, taxi, aircraft and wheelchair).

The household data files are supplemented with vehicle data files which contain records for all vehicles in each household. Data fields include vehicle body type, vehicle make and model, year of manufacture, registration (private vs. business use) and ownership (owned by household member, by company or by other).

The person data files include records for all participating members of each household, approximately 5,800 persons per annual wave. Data fields include: gender, age, relation to the household head (defined as the main HTS respondent in the household), occupation, student status, employment status, type of work hours, type of work day, employer’s assistance with travel, main mode of travel to work, main job location, driving licence status, personal income, mobility restriction status, and fields indicating whether trip details were completed with aid or by proxy interview with an adult member of the household.

The travel diary files include all ‘stops’ made by the respondents for the 24-h from 4 am on the survey day to 4 am of the following day. When interviewed, the term ‘stop’ is used to ensure that respondents focus on activities rather than trips as such. The stop may be defined as a ‘separate travel movement’ or a ‘trip’ with the purpose of changing mode, serving passenger or going to an activity site. The more common term ‘trip’ is subsequently used and the travel diary files are referred to as unlinked trips which include approximately 30,000 trips per annual wave. For each unlinked trip, the information collected includes the departure and arrival times, travel purpose (22 activity types), trip origin and destination (recorded as addresses and geo-coded to travel zone), mode of travel, distance travelled, type of fare, type of ticket, cost of fare, parking cost, parking payment method and frequency, the number of people in the car, and the number of household members in the car. The last two data fields are applied for car trips only.

These four data files all have the key fields that uniquely identify each household, person, vehicle, trip and home-based tour. Household, person and home-based tour identification data
fields help connect these four data files when restructuring the data to identify joint household travel and home-based tours discussed in Chapter 4.

3.2.2 Transport network data: Sydney Strategic Travel Model

The Sydney 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, tolls (if applicable) 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 public transport combined modes in the am-peak, for the 2,690 travel zones across the Sydney GMA with 2,277 travel zones in Sydney SD. The skim matrices are available in 5-year intervals from 2006 to 2036 and this study uses data for the year 2006. The Sydney STM uses an ‘equilibrium solution’ for car and an ‘optimal strategy’ for public transport in the assignment process (BTS, 2011b). The equilibrium solution assumes that the route with the lowest cost is used between each origin and destination pair until congestion occurs when alternative routes are used to the extent that they have an equal cost to the most economic route. Similarly, the optimal strategy assumes that public transport users choose the route or routes with minimum expected travel time (including in-vehicle, waiting and walking times).

Nine possible ways of travel from one travel zone to another are represented explicitly in the system: car driver, car passenger, train, light rail, ferry, bus, bicycle, walk and taxi. To reflect the reality, the Sydney STM restricts the availability of possible travel modes between each zone pair. More specifically, not all modes are available for travel between each zone pair and train, bus and taxi modes are not considered available for intra-zonal travel.

The level of service data for intra-zonal travel are not available from the Sydney STM and are estimated in this thesis based on individual trip distances recorded in the HTS and the average travel speed of 5 km/h for walking and 30 km/h for car mode (BTS, 2011a). Also, the public transport level of service data for periods of the day other than the am-peak (7 am to 9 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. On the one hand, the wait time multiplier for a certain time of day period can be derived by comparing the public transport service timetable during that period of the day with the public transport service timetable during the am-peak. On the other hand, the multipliers for on-board travel time are equal to the ratio of car travel time during the time of day in question to car travel time during the am-peak for the same origin-destination pair. This assumption is supported by the way off-peak public transport services in Sydney are dominated by bus services and buses share the same
road space with cars (dedicated bus lanes account for a minor proportion of total bus routes). The network performance data on weekend are estimated from matching weekend traffic volumes and public transport timetables to weekday patterns. Table 3.3 shows the multipliers used to calculate the average waiting time for all periods outside the am-peak on weekdays. The multipliers for on-board travel time are not shown because they are different across each origin and destination pair. The imputed on-board travel times for a number of origin and destination pairs are compared with the timetable values from the 131500 Transport Infoline (www.131500.com.au). The results suggest that the imputed on-board times are quite consistent with the timetable travel times.

Table 3.3 Multipliers to waiting time in am-peak for different time of day periods

<table>
<thead>
<tr>
<th>Time of day</th>
<th>Period</th>
<th>Average headway</th>
<th>Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekday</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am-peak</td>
<td>7 am – 9 am</td>
<td>10 minutes</td>
<td>1.0</td>
</tr>
<tr>
<td>Inter-peak</td>
<td>9 am – 3 pm</td>
<td>15 minutes</td>
<td>1.5</td>
</tr>
<tr>
<td>Pm-peak</td>
<td>3 pm – 6 pm</td>
<td>15 minutes</td>
<td>1.5</td>
</tr>
<tr>
<td>Evening</td>
<td>6 pm – 9 pm</td>
<td>20 minutes</td>
<td>2.0</td>
</tr>
<tr>
<td>Night</td>
<td>9 pm – 7 am</td>
<td>30 minutes</td>
<td>3.0</td>
</tr>
<tr>
<td>Weekend</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morning</td>
<td>8 am – 10 am</td>
<td>20 minutes</td>
<td>2.0</td>
</tr>
<tr>
<td>Peak</td>
<td>10 am – 4 pm</td>
<td>20 minutes</td>
<td>2.0</td>
</tr>
<tr>
<td>Off-peak</td>
<td>4 pm – 7 pm</td>
<td>20 minutes</td>
<td>2.0</td>
</tr>
<tr>
<td>Evening</td>
<td>7 pm – 8 am</td>
<td>30 minutes</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*Public transport headway is defined as the time between two consecutive services on the same route.*

### 3.2.3 Land use data

In addition to the HTS and network data, the Bureau of Transport Statistics provided land use data measured at the individual-level and household-level. The zonal attributes are also provided for the 2,690 travel zones in the Sydney GMA in Geographical Information System (GIS) layers. The individual-level land use data includes walking distance from workplace (for workers only) and school (for students only) to the closest bus stop; distance between home and school, home and workplace, workplace and school, and between workplaces (for dual worker households). The land use data at the household-level includes 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. All individuals within a same household residing at a specific location have the same access distance to the closest high frequency public transport.
node. All of these distance variables are measured using the road distance and the real X and Y coordinates of the home, school and workplace.

Other dimensions of land use are 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 (non-holiday, non-weekend day) from 6 am to 10 am, the extended am-peak. Accessibility to the Sydney CBD is extracted from the GIS layer showing the public transport travel time to reach the Sydney CBD while access to local facilities can be derived from the GIS layers showing locations of schools and shopping centres. The travel zone layer showing zone boundaries and centroids with zone attributes, including population and total employment by industry, is used to compute density and diversity of mixed land use. Finally, the road network layer is used to retrieve street layout measures or design aspects of the road network. All GIS layers are from the year 2006. This is because the Sydney HTS data used in this study are based on the 2006 zoning system.

The level of service data and zone attributes were added to the travel diary files by matching the skim matrices and land use data with the travel diaries. To do this, the trip departure and arrival times in the travel diaries were recoded to four periods (am-peak, inter-peak, pm-peak and evening) and used alongside the trip origin and destination to match with the skim matrices. Land use data at the individual and household levels were matched by person and household identifiers while those at the travel zone level were matched by the trip origin and destination coded to travel zone. As all waves of the 3 years pooled data (2007/2008, 2008/09 and 2009/10) were based on the same 2006 zoning system and changes to network performance and land use from 2006 and 2011 are relatively small, any error resulting from the assignment of 2006 network and land use data to the travel diary data should be minor.

3.3 Classification of Intra-Household Interactions
Chapter 2 outlined a number of ways that have been used in the literature to represent intra-household interactions in relation to travel behaviour. A typical method employed in studies on short-term activity-travel decisions with intra-household interactions is to classify and model different patterns of joint household activity and travel. A classification scheme can be as simple as a binary taxonomy of joint vs. solo activity/trip (e.g., Scott and Kanaroglou, 2002) but can also be very detailed with the dimensions including travel purpose, number of tours and joint tour structure (e.g., Gliebe and Koppelman, 2005). The adopted classification
needs to consider the purpose of the study or application and has to be simple and clear to make it useful and applicable; yet travel behaviour is so complex that any taxonomy is admittedly limited (Krizek, 2003).

From the viewpoint of activity-based travel demand, Vovsha et al. (2003) suggest that a taxonomy system should distinguish three key categories of joint household travel for a better understanding of the underlying travel generation mechanism. These are joint travel generated by the desire to participate in joint activities which exclusively imply a fully joint tour structure for non-subsistence activities (i.e., non-work, non-education); joint travel motivated by the synchronization of individual subsistence activities without a joint engagement in the activity; and finally joint travel which arises when an adult household member or members escort children to school. This implies that at the stage of the mode choice decision, activities have already been generated, and thus escorting and shared rides without joint participation in an activity (the second and third categories above) can be combined in modelling mode choice (Vovsha and Petersen, 2005; Yarlagadda and Srinivasan, 2008a).

Building on these previous studies, this thesis develops a typology of tours to distinguish different patterns of joint household travel based on tour structure and the implied intra-household interactions. Intra-household interactions are identified as patterns of intra-tour cooperation between/among household members that reflect different ways of arranging household activities and travel into a home-based tour, defined as a sequence of trips starting and ending at the individual’s home. Joint household activities and shared rides are recognised as part of the joint decision making process that influences the travel patterns of each household member as these joint activities and travel imply household members have agreed upon time and space constraints for the journey. The next section describes the modelling approach before turning to the identification of joint household travel from the Sydney HTS data.

3.4 Discrete Choice Modelling Approaches

Chapter 2 has reviewed a variety of modelling approaches used in the literature to investigate intra-household interactions and group decisions. The choice of a modelling approach is driven by the type of the dependent variable. That is, whether the dependent variable is a discrete choice, a continuous choice, or a combination of discrete and continuous aspects of the choice. As this study focuses on joint household travel arrangements and mode choice decisions which are both discrete in nature, the choice of discrete choice models is
straightforward. This section describes different discrete choice models that can be applied to analyse intra-household interactions in travel mode choice. The following description and discussion are drawn from the works of McFadden (1978), Ben-Akiva and Lerman (1985), Train (2009) and Gliebe and Koppelman (2005).

### 3.4.1 Generalised extreme value (GEV) models

Discrete choice models estimated in this thesis are based on random utility theory that employs an assumption that a decision maker, faced with a choice among a set of options, will choose an alternative that provides the greatest utility (or highest level of satisfaction) for them. The decision maker can be an individual, a household, or a firm. The utility obtained by decision maker $n$ from each alternative $j$ available in their choice set with $J$ alternatives is denoted as $U_{nj}$, $j = 1, ..., J$. The researcher does not observe this utility but does observe some attributes of the alternatives and characteristics of the decision maker. The utility is therefore postulated to have both observable component, $V_{nj}$ and unobserved component, $\varepsilon_{nj}$, given as:

$$U_{nj} = V_{nj} + \varepsilon_{nj}, \; j = 1, ..., J$$  \hspace{1cm} (3.1)

Under the assumption of utility-maximising behaviour, a decision maker $n$ chooses alternative $i$ if and only if $U_{ni} > U_{nj}$ $\forall j \neq i$. The probability that the decision maker $n$ chooses alternative $i$ is therefore:

$$P_{ni} = P(U_{ni} > U_{nj}, \forall j \neq i) = P(V_{ni} + \varepsilon_{ni} > V_{nj} + \varepsilon_{nj}, \forall j \neq i)$$

$$= P(\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj}, \forall j \neq i)$$  \hspace{1cm} (3.2)

Treating $\varepsilon_{nj}\forall j$ as random terms with a joint density function $f(\varepsilon_{nj})$, the probability expression in Equation (3.2) is a cumulative distribution such that each random term $\varepsilon_{nj} - \varepsilon_{ni}$ is below the observed utility $V_{ni} - V_{nj}$ and can be rewritten as:

$$P_{ni} = \int_{\varepsilon} I(\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj}, \forall j \neq i) f(\varepsilon_n) d\varepsilon_n$$  \hspace{1cm} (3.3)

where $I(\cdot)$ is the indicator function which equals one when the term in parentheses is true and zero otherwise (Train, 2009). This multidimensional integral will lead to different discrete choice models, depending on the assumptions which are made about the joint distribution of the unobserved component of utility. Some models have a closed form, with the integral being calculated exactly from the mathematical formula while other models do not have such a closed form and are evaluated numerically by simulation.
The popular logit model (also known as multinominal logit or MNL model) is obtained by assuming that each random component $\varepsilon_{nj}$ is an independently and identically distributed extreme value (or iid Gumbel and type I extreme value). The probabilistic choice system in Equation (3.3) results in a closed-form expression (Train, 2009):

$$P_{ni} = \frac{\exp(V_{ni})}{\sum_{j} \exp(V_{nj})}$$

(3.4)

Observable utility is usually (but not necessarily) specified to be linear-in-parameters, $V_{ni} = \beta X_{ni}$ where $X_{ni}$ is a vector of observed attributes relating to alternative $i$ and decision maker $n$, and $\beta$ is a vector of parameters to be estimated.\(^1\) The probability expression in Equation (3.4) therefore becomes:

$$P_{ni} = \frac{\exp(\beta X_{ni})}{\sum_{j} \exp(\beta X_{nj})}$$

(3.5)

The vector $\beta$ containing the parameters of the model is estimated statistically using maximum likelihood estimator. Manski and McFadden (1981) and Train (2009) describe estimation methods under a variety of sampling procedures. Under the situation where the sample is exogenous to the choice being analysed and where each decision maker’s decision is independent from that of other decision makers, a likelihood function is defined as the product of the probability of each decision maker in the sample choosing the alternative that they were observed to actually choose, given as:

$$L(\beta) = \prod_{n=1}^{N} \prod_{i} (P_{ni})^{y_{ni}}$$

(3.6)

where $y_{ni}$ is an indicator, equalling one if individual $n$ chose alternative $i$ and zero otherwise.

As the probability $P_{ni}$ is necessarily between zero and one, the likelihood function expressed in Equation (3.6) approaches zero when $N$ increases. Estimations therefore work with the log-likelihood function instead and the estimator is the value of $\beta$ that maximises this function:

\(^1\) Mathematically, the transpose of a vector $\beta$, denoted as $\beta'$ is usually used in the expression $V_{ni} = \beta' X_{ni}$ as $\beta'$ is conformable with $X_{ni}$ for matrix multiplication. To simplify the notation, $\beta$ is used throughout this thesis.
Here, the linear-in-parameter specification helps in the numerical maximising procedures and McFadden (1974) shows how this log-likelihood function is globally concave in parameters $\beta$. The log-likelihood function of other model specifications, for example nonlinear utility or more flexible models discussed below, may not be globally concave and results in more difficult estimation and less available computer procedures.

The MNL model is attractive as it is straightforward to estimate, use and interpret. However, the assumption about the distribution of unobserved utility underpinning the model results in a well known property of the standard logit: independence of irrelevant alternatives (IIA). That is, the ratio of choice probabilities between any pair of alternatives will remain the same regardless of the presence/absence of other alternatives and any change in an attribute of other alternatives. The former property of MNL models is well illustrated by a ‘red bus/blue bus’ example while the latter is referred to as ‘uniform cross-elasticities’ in the literature. The red bus/blue bus problem is best described by the following example. Consider a commuter with two options of travelling to work: either driving a car or riding a red bus. For simplicity assume that the choice probability of driving a car equals to that of riding a red bus such that $P_{\text{car}} = P_{\text{red bus}} = 0.5$ and the ratio of choice probabilities between car and red bus is $P_{\text{car}} / P_{\text{red bus}} = 1$. Suppose further that a blue bus is introduced and the commuter considers the blue bus to be exactly the same as the red bus. Thus, the probability that the commuter will choose the blue bus is the same as for the red bus, and the ratio of probabilities for the two bus alternatives is $P_{\text{blue bus}} / P_{\text{red bus}} = 1$. As the MNL model predicts the ratio of choice probabilities between the red bus and the car to be unchanged with the presence of the new blue bus (i.e., $P_{\text{car}} / P_{\text{red bus}} = 1$), the only choice probabilities that satisfy $P_{\text{blue bus}} / P_{\text{red bus}} = 1$ and $P_{\text{car}} / P_{\text{red bus}} = 1$ are $P_{\text{car}} = P_{\text{red bus}} = P_{\text{blue bus}} = 1/3$. In reality, the probability of driving a car would remain the same ($P_{\text{car}} = \frac{1}{2}$) and the original probability of riding a bus would split equally between the two buses ($P_{\text{red bus}} = P_{\text{blue bus}} = \frac{1}{4}$) after the introduction of the blue bus. Thus, the ratio of choice probabilities between car and red bus actually changes with the presence of the blue bus, as opposed to remaining constant as required by the MNL model.

The same kind of misprediction arises with MNL models whenever the ratio of choice probabilities between any pair of alternatives changes with a change in an attribute of another alternative. For instance, suppose there is a light rail route that runs parallel to an existing bus
route. An improvement to the light rail service with cheaper fares, for example, might be expected to reduce the probability of bus by a greater extent than it reduces the probability of car. Thus, the ratio of choice probability for car and bus changes rather than remaining constant with a change to the fare of the light rail service, an ‘irrelevant’ alternative. These examples highlight the limitations of the IIA property intrinsic to the MNL model. When the choice behaviour does not exhibit IIA, a more general model than the standard logit is required and alternative models are discussed below.

Generalised extreme value (GEV) models consist of a large class of models that allow for structural correlations in the unobserved portions of utility across alternatives. McFadden (1978) developed a process to generate GEV models that are analytically tractable (i.e., having a closed-form for the choice probabilities) and consistent with utility maximisation. This process involves a specification of a function, labelled \( G = G(Y_1, Y_2, ..., Y_J) \) that depends on \( (Y_1, Y_2, ..., Y_J) \geq 0 \) and exhibits the following properties (McFadden, 1978, pp. 80):

1. \( G \geq 0 \) for all \( Y_j \geq 0 \).
2. \( G(\rho Y_1, \rho Y_2, ..., \rho Y_J) = \rho G(Y_1, Y_2, ..., Y_J) \). That is, \( G \) is homogenous of degree one.
3. \( \lim_{Y_i \to +\infty} G(Y_1, Y_2, ..., Y_J) = +\infty \) for all \( i = 1, ..., J \).
4. For any distinct \( (i_1, i_2, ..., i_k) \) from \( \{1, 2, ..., J\} \), \( \frac{\partial^k G}{\partial Y_{i_1} \partial Y_{i_2} ... \partial Y_{i_k}} \) is nonnegative if \( k \) is odd and non-positive if \( k \) is even.

If \( G \) satisfies these conditions, then
\[
P_i = \frac{Y_i G_i}{G}, \text{ where } G_i = \frac{\partial G}{\partial Y_i}
\]
and (3.8) defines the choice probabilities of alternatives \( i = (1, 2, ..., J) \) for a discrete choice model that is consistent with utility maximisation.

This procedure can be used to derive different GEV models identified in the literature (e.g., standard logit, nested logit, cross nested logit, generalised nested logit) and to develop new GEV models that best fit specific circumstances. Nested logit is the most widely used member of the GEV family with alternatives faced by a decision maker being partitioned into non-overlapping subsets or nests. A two-level nested logit can be derived from the following generating function:
\[
G = \sum_{m=1}^{M} \left( \sum_{j \in m} Y_j^{1/\lambda_m} \right)^{\lambda_m}, \lambda_m \in (0,1) \text{ and } Y_j = \exp(V_j)
\]
Train (2009) shows that this function has the necessary properties described above and that the choice probability for the two-level nested logit can be decomposed into two standard logit probabilities, expressed as:

\[
P_{ni} = P_{nm} P_{nj/m}
\]

(3.10)

where \( P_{nm} \) is the marginal probability that decision maker \( n \) chooses nest \( m \), and \( P_{nj/m} \) is the probability that decision maker \( n \) chooses alternative \( i \) conditional on choosing nest \( m \). The marginal and conditional probabilities can be expressed as:

\[
P_{nm} = \frac{\exp(W_{nm} + \lambda_m I_{nm})}{\sum_{l} \exp(W_{nl} + \lambda_l I_{nl})}
\]

(3.11)

\[
P_{nj/m} = \frac{\exp(Z_{ni} / \lambda_m)}{\sum_{j \in m} \exp(Z_{nj} / \lambda_m)}
\]

(3.12)

where observed utility \( V_{nj} \) is decomposed into two parts, \( W_{nm} \) and \( Z_{nj} \), defined as follows:

\( W_{nm} \) is a portion of observed utility that varies over nests but not over alternatives within each nest;

\( Z_{nj} \) is a portion of observed utility that varies over alternatives within each nest;

\( I_{nm} = \ln \sum_{j \in m} \exp(Z_{nj} / \lambda_m) \) is inclusive value of nest \( m \); and

\( \lambda_m \) is inclusive value parameter that reflects the level of independence among the unobserved portions of utility for alternatives within nest \( m \). All inclusive value parameters need to range in between zero and one to be consistent with utility maximisation with a higher \( \lambda_m \) indicating more independence (less correlation) among alternatives within that nest. When \( \lambda_m \) equals one for all nests, a nested logit collapses to the standard logit model.

For a two-level nested logit model, it is typical to refer to the marginal probability given in Equation (3.11) as the ‘upper level’ and to the conditional probability in Equation (3.12) as the ‘lower level’. The inclusive value \( I_{nm} \) can then be interpreted as the link between the two levels while the product of inclusive value and its parameter, \( I_{nm} \lambda_m \) is the expected maximum utility that decision maker \( n \) obtains from the choice among the alternatives in nest \( m \) (Ben-Akiva and Lerman, 1985; Train, 2009). Nested logit models with three or more levels can be decomposed into a series of standard logit probabilities and interpreted in a similar way.

For the nested logit, the IIA property still holds within each nest but not for alternatives in different nests. Also, alternatives within the same nest are highly substitutable for each other as compared to alternatives in different nests. In other words, cross-elasticities are greater
between pairs of alternatives in the same nest than between pairs of alternatives in different nests. This can be seen by comparing cross-elasticities of the nested logit model shown in Table 3.4 where elasticities of the logit model are also provided, both with the observed utility being specified as linear in parameters (Ben-Akiva and Lerman, 1985). Elasticity in discrete choice model has the normal interpretation of the percentage change in the choice probability of a particular alternative with respect to a one percent change in an attribute of an alternative, ceteris paribus. If the change occurs in an attribute of the alternative whose change in choice probability is being measured, the elasticity is referred to as direct elasticity. A cross-elasticity, on the other hand, measures the percentage change in the choice probability of a particular alternative with respect to one percent change in an attribute of a competing alternative (Louviere et al., 2000, p80). The elasticity of the probability of alternative \(i\) for decision maker \(n\) with respect to a marginal change in variable \(k\) entering the utility of alternative \(i, x_{ikn}\) (direct elasticity) and alternative \(j, x_{jkn}\) (cross-elasticity) are given as:

\[
E_{x_{ikn}}^{P_{ni}} = \frac{\partial P_{ni}}{\partial x_{ikn}} x_{ikn} / P_{ni}
\]

\[
E_{x_{jkn}}^{P_{ni}} = \frac{\partial P_{ni}}{\partial x_{jkn}} x_{jkn} / P_{ni}
\]

Substituting Equations (3.5) and (3.10) respectively into (3.13) and (3.14) produces the direct and cross-elasticities of the logit and nested logit models shown in Table 3.4.

Table 3.4 Direct and cross-elasticities of the logit (MNL) and nested logit (NL) models

<table>
<thead>
<tr>
<th>Model</th>
<th>Direct elasticity (E_{x_{ikn}}^{P_{ni}})</th>
<th>Cross-elasticity (E_{x_{jkn}}^{P_{ni}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNL</td>
<td>((1 - P_{ni}) \beta_{ik} x_{ikn})</td>
<td>(-P_{nj} \beta_{jk} x_{jkn})</td>
</tr>
<tr>
<td>NL</td>
<td>([(1 - P_{ni}) + (1/\lambda_m - 1)(1 - P_{ni/m})] \beta_{ik} x_{ikn})</td>
<td>(-P_{nj} \beta_{jk} x_{jkn}) if (i \in m, j \in l, m \neq l)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-[P_{nj} \beta_{jk} x_{jkn} + (1/\lambda_m - 1)P_{nj/m} \beta_{jk} x_{jkn}] = [-P_{nj} + (1/\lambda_m - 1)P_{nj/m}] \beta_{jk} x_{jkn}) if (i, j \in m)</td>
</tr>
</tbody>
</table>


Because elasticity measures are unit free and the aggregate probability of an alternative can be interpreted as its share of the market, elasticities are useful in measuring the average response to transport policy or a change to some factor (Train, 2009). The measure of central tendency used to calculate the ‘average’ response requires a method of aggregating individual
elasticities given in Equations (3.13) and (3.14). There exist three aggregation methods including the use of sample averages and average estimated probabilities, naive pooling (elasticities are aggregated from individual elasticities but not weighted by their choice probability), and probability weighted sample enumeration (PWSE). In line with choice modelling methodology, the PSWE technique is used in this study with the aggregate elasticities being expressed as follows (Louviere et al., 2000):

$$E_{X_{jk}} = \sum_{n=1}^{N} \frac{P_{ni}P_{ni}}{\sum_{n=1}^{N} P_{ni}}$$  \hspace{1cm} (3.15)

3.4.2 Parallel choice constrained logit

The GEV family of models discussed above are founded on the individual behaviour as the decision maker. Although a household can be treated as a decision maker, the GEV family of models assume a household as a homogeneous group and thus do not provide a straightforward interpretation in terms of group decisions. Based on the McFadden’s procedure described above, Gline and Koppelman (2005) developed a model, called parallel choice constrained logit, to account for multiple decision makers. The following function is used to generate this joint decision model with two decision makers $n$ and $n'$:

$$G(Y_{1n}, Y_{2n}, \ldots, Y_{Jn}, Y_{1'n}, Y_{2'n}, \ldots, Y_{J'n}) = \sum_{m=1}^{M} \left[ \sum_{j \in C_{nm}} Y_{jn}^{\lambda_{m}} \left( \sum_{j' \in C_{n'm}} Y_{j'n'}^{\lambda_{m}} \right) \right]^{\theta_{n}}$$  \hspace{1cm} (3.16)

where:

- $Y_{jn} \equiv \exp(V_{jn}), \forall j$ and $Y_{j'n'} \equiv \exp(V_{j'n'}), \forall j'$;
- $C_{nm}$ and $C_{n'm}$ represent the choice sets of decision makers $n$ and $n'$ given their joint choice $m$;
- $\theta_{n}$ and $\theta_{n'}$ are importance weights of decision makers $n$ and $n'$ relative to the joint decision;

Gline (2004) shows that the generating function in (3.16) exhibits the properties listed above if $\theta_{n} + \theta_{n'} = 1$ and $\lambda_{m} \geq 1$. The probabilistic choice model that is consistent with utility maximisation is defined by:

$$P_{in} = \frac{Y_{in}G_{in}}{\theta_{n}G}, \text{ where } G_{in} = \frac{\partial G}{\partial Y_{in}}$$  \hspace{1cm} (3.17)

$$P_{i'n'} = \frac{Y_{i'n'}G_{i'n'}}{\theta_{n}G}, \text{ where } G_{i'n'} = \frac{\partial G}{\partial Y_{i'n'}}$$  \hspace{1cm} (3.18)
These choice probabilities are slightly different from McFadden’s original description in which Equations (3.17) and (3.18) take individual importance weights into consideration. Through an algebraic manipulation, Gliebe (2004) shows Equations (3.17) and (3.18) lead to the following choice probabilities:

\[
P_{in} = \frac{\exp(\lambda_m V_{in}) \cdot \exp \left( \frac{\theta_n I_{nm} + \theta_n' I_{n'm}}{\lambda_m} \right)}{\sum_{j \in C_{nm}} \exp(\lambda_m V_{jn}) \cdot \sum_{m=1}^{M} \exp \left( \frac{\theta_n I_{nm} + \theta_n' I_{n'm}}{\lambda_m} \right)}
\]

(3.19)

\[
P_{i'n'} = \frac{\exp(\lambda_m V_{i'n'}) \cdot \exp \left( \frac{\theta_n I_{nm} + \theta_n' I_{n'm}}{\lambda_m} \right)}{\sum_{j' \in C_{n'm}} \exp(\lambda_m V_{j'n'}) \cdot \sum_{m=1}^{M} \exp \left( \frac{\theta_n I_{nm} + \theta_n' I_{n'm}}{\lambda_m} \right)}
\]

(3.20)

where

\[
I_{nm} = \ln \sum_{j \in C_{nm}} \exp(\lambda_m V_{jn}) \quad ; \quad I_{n'm} = \ln \sum_{j \in C_{n'm}} \exp(\lambda_m V_{j'n'})
\]

The quantities \( I_{nm} \) and \( I_{n'm} \) are conventionally interpreted as inclusive values that decision makers \( n \) and \( n' \) obtain from their joint choice \( m \), while their weighted sum represents the total utility to be derived by the two decision makers. Also, the inverse of \( \lambda_m \) parameters, which Gliebe and Koppelman (2005) term nesting parameters, are equivalent to inclusive value parameters in a nested logit. Thus, the ratio of \( I_{nm} \) to \( \lambda_m \) can be interpreted as the expected maximum utility that person \( n \) obtains from joint choice \( m \), and similarly for person \( n' \). However, the probabilistic model expressed in Equations (3.19) and (3.20) are different from the nested logit model in the sense that it applies to choice situations with multiple persons involved and requires the same joint choice for all decision makers. This requirement is guaranteed by imposing the following constraint on the model specification.

\[
\sum_{i \in m} \Pr(Y_{inn} = 1) = \sum_{i' \in m} \Pr(Y_{i'n'm} = 1), \quad \forall m
\]

(3.21)

where \( Y_{inn} = 1 \) indicates that person \( n \) chooses alternative \( i \) and \( Y_{i'n'm} = 1 \) indicates that person \( n' \) chooses alternative \( i' \), both individual choices satisfy the same joint choice \( m \). As a result of this overarching joint choice constraint imposed on multiple decision makers acting in parallel, Gliebe and Koppelman (2005) term the model system as the parallel choice constrained logit. The constraint specified in Equation (3.21) is expressed in words as (Gliebe and Koppelman, 2005, p. 458):
“The sum of the probabilities of the alternatives comprising an individual’s choice set for a particular joint outcome must equal the sum of the probabilities of the alternatives available in the choice set of his/her fellow decision maker for the same joint outcome.”

In an application to analyse interactions between the two household heads, Gliebe and Koppelman (2005) classify individual daily activity pattern alternatives (choice variable) so that each alternative satisfies only one joint choice and use a predefined tree structure to enforce the constraint specified in (3.21). In multiple person households, however, an individual choice may satisfy more than one joint household choice and this makes the constraint specified in (3.21) very difficult to meet with a predefined tree structure approach as there are many joint travel combinations. In a 3-person household, for example, each member can have an individual daily travel pattern where the joint household travel outcome is independent, any pair can have a joint travel arrangement while the third person travels individually giving rise to a joint household decision which is fully joint by two persons, or the three household members can take a fully joint travel arrangement so that a joint household decision can be classified as fully joint by all household members. The individual daily travel pattern in the examples given above belongs to two different joint household outcomes: an independent pattern and one which is fully joint by two persons. This calls for an alternative approach to modelling group decisions and intra-household interactions in households with multiple persons.

3.4.3 Generalised parallel choice constrained logit

Rather than using a predefined tree structure to ensure the structural constraint specified in (3.21) is met, a more appropriate approach may use the allocation of a parameter $\alpha_{jnm}$ that characterises the portion of alternative $i$ assigned to joint household choice $m$ (or the probability that individual alternative $i$ belongs to joint household outcome $m$). The modified generating function for joint household model that allows an individual alternative to belong to multiple joint outcomes is:

$$G(Y_{1n}, Y_{2n}, \ldots, Y_{jn}; Y_{1n'}, Y_{2n'}, \ldots, Y_{jn'}) = \sum_{m=1}^{M} \left[ \sum_{j \in C_{nm}} \left( \sum_{j \in C'_{nm}} \left( \alpha_{jnm} Y_{jn} \right) \right)^{2} \left( \sum_{j \in C'_{nm}} \left( \alpha_{j'n'm} Y_{jn'} \right)^{2} \right)^{1/2} \right]^{1/2}$$

where:

$$\alpha_{jnm} \geq 0, \forall j \text{ and } \sum_{m} \alpha_{jnm} = 1, \forall j; \; \alpha_{j'n'm} \geq 0, \forall j' \text{ and } \sum_{m} \alpha_{j'n'm} = 1, \forall j';$$

Other notations are same as above.
The modified generating function exhibits the same properties as the parallel choice constrained logit (PCCL) model developed by Gliebe and Koppelman (2005) described above. In particular, the generating function possesses the following properties to be consistent with McFadden’s (1978) original GEV model derivation.

- \( G \) is non-negative for all non-negative \( Y_{jn} \equiv \exp(V_{jn}), \forall j \) and \( Y_{j'n'} \equiv \exp(V_{j'n'}), \forall j' \);
- \( G \) is homogenous of degree one if \( \theta_n + \theta_{n'} = 1 \). This can be proved by substituting \( Y_{jn} \) in Equation (3.22) with \( \rho Y_{jn} \), such that:

\[
G(\rho Y_{1n}, \rho Y_{2n}, \ldots, \rho Y_{jn}; \rho Y_{1n'}, \rho Y_{2n'}, \ldots, \rho Y_{jn'}) = \sum_{m=1}^{M} \left[ \sum_{j \in \mathcal{C}_{nm}} \left( \alpha_{jnm} \rho Y_{jn} \right)^{\lambda_m} \right]^{\theta_n} \cdot \left[ \sum_{j' \in \mathcal{C}_{n'm}} \left( \alpha_{j'n'm} \rho Y_{j'n'} \right)^{\lambda_m} \right]^{\theta_{n'}} \cdot \rho^{\frac{1}{\lambda_m}}}
\]

(3.23)

As \( \theta_n \) represents the importance weight or power of individual \( n \) in the joint household decision, it is also required that \( \theta_n \geq 0, \forall n \). These conditions provide the generating function not only a necessary property to be consistent with utility maximisation but also a useful interpretation in which a household member may not involve in the joint decision \( (\theta_n = 0) \) while all participants’ importance weights sum to one.

- \( \lim_{Y_{jn} \to +\infty} G(Y_{1n}, Y_{2n}, \ldots, Y_{jn}) = +\infty \) for \( \forall i = 1, \ldots, J \); and
- \( \lim_{Y_{jn'} \to +\infty} G(Y_{1n'}, Y_{2n'}, \ldots, Y_{jn'}) = +\infty \) for \( \forall i' = 1, \ldots, J' \).

- For any distinct alternative \( (i_1, i_2, \ldots, i_k) \) from the choice set of a single decision maker \( \{1, 2, \ldots, J\} \), \( \frac{\partial^k G}{\partial Y_{i1} \partial Y_{i2} \ldots \partial Y_{ik}} \) is nonnegative if \( k \) is odd and non-positive if \( k \) is even. This property can be verified by calculating partial derivatives. The first partial derivative is
\[ G_{in} = \frac{\partial G}{\partial Y_{in}} \]

\[ = \sum_{m=1}^{M} \left( \frac{\theta_n}{\lambda_m} \sum_{j \in C_{nm}} (\alpha_{jnm}Y_{jn})^{\lambda_m} \right)^{\theta_n-1} \lambda_m^{\lambda_m-1} \left( \sum_{j \in C'_{nm}} (\alpha_{j'n'm}Y_{j'n'})^{\lambda_m} \right)^{\theta_n} \]

\[ = \sum_{m=1}^{M} \theta_n \alpha_{inn} Y_{in}^{\lambda_m-1} \left( \sum_{j \in C_{nm}} (\alpha_{jnm}Y_{jn})^{\lambda_m} \right)^{\theta_n} \lambda_m^{\lambda_m-1} \left( \sum_{j \in C'_{nm}} (\alpha_{j'n'm}Y_{j'n'})^{\lambda_m} \right)^{\theta_n} \]

(3.24)

Since \( \theta_n \geq 0 \) \( \forall n, \alpha_{inn} \geq 0 \) \( \forall i, \) \( Y_{in} \geq 0 \) \( \forall in, \) and \( Y_{i'n'} \geq 0 \) \( \forall i'n', \) \( G_{in} \geq 0 \) as required. The second cross partial derivative with respect to alternative \( l \in C_{nm}, l \neq i \) is

\[ G_{iln} = \frac{\partial^2 G}{\partial Y_{in} \partial Y_{ln}} \]

\[ = \theta_n \cdot \sum_{m=1}^{M} \alpha_{inn} Y_{in}^{\lambda_m-1} \left( \sum_{j \in C_{nm}} (\alpha_{jnm}Y_{jn})^{\lambda_m} \right)^{\theta_n-2} \lambda_m^{\lambda_m-2} \left( \sum_{j \in C'_{nm}} (\alpha_{j'n'm}Y_{j'n'})^{\lambda_m} \right)^{\theta_n} \]

\[ = \theta_n \cdot \sum_{m=1}^{M} (\theta_n - \lambda_m) (\alpha_{inn})^{\lambda_m} (Y_{in}Y_{ln})^{\lambda_m-1} \left( \sum_{j \in C_{nm}} (\alpha_{jnm}Y_{jn})^{\lambda_m} \right)^{\theta_n-2} \lambda_m^{\lambda_m-2} \left( \sum_{j \in C'_{nm}} (\alpha_{j'n'm}Y_{j'n'})^{\lambda_m} \right)^{\theta_n} \]

(3.25)

As \( \theta_n \leq 1 \) and \( \lambda_m \geq 1, G_{iln} \leq 0 \) as required. For \( l \not\in C_{nm} \) and \( l \neq i, G_{iln} = 0 \) which also meets the non-positive criterion. Higher cross partial derivatives are calculated similarly; they exhibit the switching of signs property as required if \( \theta_n \leq 1 \) and \( \lambda_m \geq 1. \)

The probabilistic choice models that correspond to the generating function specified in Equation (3.22) are derived using Equation (3.17). Substituting Equation (3.24) into Equation (3.17) leads to the following choice probability for alternative \( i \in C_{nm}: \)
\[ P_{in} = \frac{Y_{in} G_{in}}{\theta_{n} G} \]

\[ = \sum_{m=1}^{M} \left[ \sum_{j \in C_{nm}} \left( \alpha_{jnm} Y_{jn} \right)^{\lambda_m} \theta_n \right] \left( \sum_{j' \in C_{n'm}} \left( \alpha_{j'n'm} Y_{j'n'} \right)^{\lambda_m} \theta_{n'} \right) \right]^{\lambda_m} \theta_n \theta_{n'} \]

\[ = \sum_{m=1}^{M} \left[ \sum_{j \in C_{nm}} \left( \alpha_{jnm} Y_{jn} \right)^{\lambda_m} \theta_n \right] \left( \sum_{j' \in C_{n'm}} \left( \alpha_{j'n'm} Y_{j'n'} \right)^{\lambda_m} \theta_{n'} \right) \]

\[ \text{where } P_m \text{ is the unconditional probability of joint household choice of outcome } m \text{, and } P_{in|m} \text{ is the conditional probability of person } n \text{ choosing alternative } i, \text{ given the joint household choice } m. \text{ These probabilities are expressed as follows:} \]

\[ P_m = \left( \sum_{j \in C_{nm}} \left( \alpha_{jnm} Y_{jn} \right)^{\lambda_m} \theta_n \right) \left( \sum_{j' \in C_{n'm}} \left( \alpha_{j'n'm} Y_{j'n'} \right)^{\lambda_m} \theta_{n'} \right) \]

\[ = \sum_{m=1}^{M} \left[ \sum_{j \in C_{nm}} \left( \alpha_{jnm} Y_{jn} \right)^{\lambda_m} \theta_n \right] \left( \sum_{j' \in C_{n'm}} \left( \alpha_{j'n'm} Y_{j'n'} \right)^{\lambda_m} \theta_{n'} \right) \]

\[ P_{in|m} = \frac{\alpha_{jnm} Y_{jn}}{\sum_{j \in C_{nm}} \left( \alpha_{jnm} Y_{jn} \right)^{\lambda_m}} \]

The choice probability for alternative \( i' \in C_{n'm} \) of the other person \( (n') \) in the same household can be derived in a similar manner. Specifically, the choice probability \( P_{i'n'} \) can be decomposed into components and rewritten as:

\[ P_{i'n'} = \sum_{m=1}^{M} P_{i'n'|m} P_m \]
where the unconditional probability $P_m$ in this expression remains the same as in Equation (3.27) and the conditional probability of person $n$ choosing alternative $i'$ given the household joint choice of outcome $m$, is expressed as follows:

$$P_{i'n'm} = \frac{\left(\alpha_{i'n'm}Y_{i'n'}\right)^{\lambda_m}}{\sum_{j' \in C_{nm}} \left(\alpha_{j'n'm}Y_{j'n'}\right)^{\lambda_m}} \tag{3.30}$$

The probabilistic choice system expressed in Equations (3.26) to (3.30) can be referred to as a generalised parallel choice constrained logit model. This model satisfies the structural requirement specified in Equation (3.21) of consistency in joint choice outcomes without the need to classify alternatives available in the choice set of each and all household members into one and only one joint household outcome. In other words, the generalised parallel choice constrained logit model allows individual alternatives to belong to multiple (but mutually exclusive) joint household outcomes. The mutually exclusive requirement of alternatives in the choice set of a household (or joint household outcomes) is a common property of discrete choice models (Train, 2009). The generalised PCCL will become an original PCCL when each individual alternative available in the choice set of any household member belongs to a unique joint household outcome. This is expressed as $\alpha_{jnm} = 1 \forall n$ and $\alpha_{j'n'm} = 1 \forall j'n'$.

The generalised PCCL is interpreted similarly to the original PCCL except that the allocation parameters $\alpha_{jnm}$ ($\alpha_{j'n'm}$) characterise the portion of the individual alternative $j \in C_n$ ($j' \in C_{n'}$) assigned to joint household outcome $m$. This can be seen by defining the following individual composite utilities for each joint household outcome $m$:

$$I_{nm} = \ln \sum_{j \in C_{nm}} \left(\alpha_{jnm}Y_{jn}\right)^{\lambda_m} = \ln \sum_{j \in C_{nm}} \left[\alpha_{jnm}\exp(V_{jn})\right]^{\lambda_m}$$

$$I_{n'm} = \ln \sum_{j' \in C_{n'm}} \left(\alpha_{j'n'm}Y_{j'n'}\right)^{\lambda_m} = \ln \sum_{j' \in C_{n'm}} \left[\alpha_{j'n'm}\exp(V_{j'n'})\right]^{\lambda_m} \tag{3.31}$$

Substituting the composite utilities defined in (3.31) into Equation (3.27), the unconditional probability can be rewritten as:

$$P_m = \frac{\exp\left(\frac{\theta_n I_{nm} + \theta_{n'} I_{n'm}}{\lambda_m}\right)}{\sum_{m=1}^{M} \exp\left(\frac{\theta_n I_{nm} + \theta_{n'} I_{n'm}}{\lambda_m}\right)} \tag{3.32}$$

Then substituting equations (3.32) and (3.28) into equation (3.26), the choice probability for alternative $i \in C_{nm}$ can be rewritten as:
Thus, the generalised PCCL maintains separate probability expressions for each household members participating in a joint household decision. As with the original PCCL model, household members derive their own expected utility shown in Equation (3.31) and the weighted sum of all members of the household represents the total utility derived by the whole household. The individuals’ weights \( \theta_n \) and \( \theta_{n'} \) can also be parametrically formulated so as to explore which individual characteristics and situational factors are associated with their relative influences in household decisions (Gliebe and Koppelman, 2005).

### 3.5 Evaluation of Modelling Approaches

Table 3.5 compares and contrasts the individual-based (represented by the nested logit) with the group-based (PCCL) modelling approaches described above. The two approaches share common features in terms of data requirements and their ability to incorporate joint household activity and travel. However, only the group-based approach is able to account for individuals’ relative influences or importance weights in the household decision. While the group-based modelling approach can deal with choice situations where decision-makers are unknown (reflected through the importance weight parameter \( \theta_n \) in Eq. (3.23), p. 73), the individual-based modelling approach facilitates predictions and policy analyses because it can incorporate a variety of joint household travel patterns. Both approaches have their own drawbacks. The group-based modelling approach is difficult to estimate because the complexity of the model structure increases with variation in household size and joint household travel outcome, resulting in a large number of elemental alternatives in the choice system. The individual-based modelling approach meets the difficulties of incorporating interdependent decisions of household members but cannot quantify the influence of each person on the joint household decision.
Table 3.5 A comparison between group and individual decision modelling approaches

<table>
<thead>
<tr>
<th>Pros</th>
<th>Group-based approach</th>
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<tbody>
<tr>
<td></td>
<td>• Interdependent choices are modelled explicitly</td>
</tr>
<tr>
<td></td>
<td>• Individuals’ importance weights can be quantified</td>
</tr>
<tr>
<td></td>
<td>• Ability to deal with choice situation where decision-maker is unknown</td>
</tr>
<tr>
<td></td>
<td>• Intra-household interactions are examined explicitly</td>
</tr>
<tr>
<td></td>
<td>• A variety of joint household travel patterns can be incorporated</td>
</tr>
<tr>
<td></td>
<td>• Facilitates predicting purposes</td>
</tr>
<tr>
<td>Cons</td>
<td>Group-based approach</td>
</tr>
<tr>
<td></td>
<td>• Model structure is very sensitive to household size and the number of joint travel patterns considered</td>
</tr>
<tr>
<td></td>
<td>• Less frequent travel patterns (potentials for interaction) are ‘cleaned’</td>
</tr>
<tr>
<td></td>
<td>• Model estimation and application is difficult and expensive in time</td>
</tr>
<tr>
<td></td>
<td>• Difficulty in integrating inter-dependent decisions</td>
</tr>
<tr>
<td></td>
<td>• Cannot quantify individuals’ importance weights</td>
</tr>
</tbody>
</table>

Thus, the main difference between the two modelling approaches is the decision-making unit and the way of incorporating intra-household interactions. The group-based approach considers the household as the decision-making unit with different household members playing different roles and collectively determining behaviour. This approach requires individual daily travel mode choice patterns to be constructed subject to joint household choice constraints. In contrast, the individual-based approach considers the individual as the decision-making unit and needs to integrate intra-household interactions in travel mode choices.

To satisfy these requirements, a tour-based coding scheme can be used for the group decision modelling approach while a typology of joint household tours is needed for the individual decision modelling approach. The tour-based coding scheme adopted for the group-based approach must exhibit the consistencies in travel pattern across all household members as discussed in Section 3.4. This requirement is difficult to meet for multiple-person households with complex joint travel patterns when, for example, a joint tour type is relevant to two tours of one person but one tour of another. Shared rides are a typical example when the chauffeur returns home in between rides, forming two separate tours while the passenger makes only one tour. To overcome this issue, the group decision approach has to code and model the entire daily tour-based travel patterns as opposed to the common practice of modelling the travel mode for each tour. Moreover, complex travel patterns which are typically less frequent but nevertheless have potential for interaction have to be ‘cleaned’ for modelling purposes. Consequently, the link between the modelling outcomes and policy implications may not be as straightforward for the group-based approach. Conversely, the individual decision
modelling approach can incorporate a variety of joint household travel patterns but this approach does not directly model the collective decision of household members on joint activity and travel arrangements.

Each modelling approach answers a slightly different set of research questions but both approaches are able to test the research hypotheses identified in Section 2.6. Ideally, the group-based modelling approach should be used because of its ability to deal with joint household decisions and quantify the individuals’ weights in the joint decision. However, the choice of a modelling approach has to consider the practical implementation and the usefulness of results. As the aim of this research is to investigate the extent of intra-household interactions and inform transport policy and planning practices for sustainable transport choices, it is preferred to keep the link between individuals’ travel mode choices and exogenous variables as simple as possible. In this regard, the group-based approach is deficient in failing to give explicit links between joint household travel and its implications for transport policy and planning practices. This is because the group-based approach considers a series of tours comprising an individual’s daily travel as the dependent variable (see Gliebe and Koppelman, 2005) while changes to transport policy usually have different influence on those tours. The individual decision modelling approach is flexible in defining general patterns of intra-tour coordination between/among household members, and therefore is more suitable for this aspect of the research. Both approaches require a typology of joint household tours that capture various patterns of intra-household interactions in travel mode choice. The typology of tours is developed and described next in Chapter 4. Chapter 5 provides a descriptive analysis of joint household travel in Sydney SD and compares joint household travel by different dimensions across countries. The typology of joint household tours is then embedded in the empirical models estimated in Chapter 6 to examine joint household travel arrangements and mode choices under household resource, social, temporal and spatial constraints.
CHAPTER 4. DATA PROCESSING

Chapter 2 has identified the research hypotheses of this study and described the four main methods of collecting data for analysing interactions and group decisions. Of which, applying matching criteria to secondary data such as household travel surveys is one potential way. Chapter 2 highlighted the challenge in using these secondary data to identify joint household travel from travel diaries in the presence of data inconsistencies. Chapter 3 has described the case study of Sydney and its public transport networks, the Sydney Household Travel Survey and other data sources available for the Sydney GMA. Chapter 3 also outlined the data requirements and modelling approaches for studying intra-household interactions in travel mode choices. To this end, a typology of joint household tours is needed that allows discrete choice models to be developed which incorporate intra-household interactions through the joint household travel arrangements.

This chapter presents steps taken to transform the Sydney Household Travel Survey data into a unique dataset used for the empirical analysis of intra-household interactions as well as time and space constraints in travel mode choices. The three steps include the identification of joint household trips, the correction of inconsistent trip details reported by household members, and the identification of intra-tour joint household travel patterns. These steps are described in the first three sections of this chapter. The implications of the results of these steps for the identification and classification of joint household activities and travel are discussed. The final section provides a summary of different datasets and a typology of joint household tours proposed for this study, with a more detailed analysis of these joint household tours is provided in Chapter 5 which serves as a precursor to modelling joint household travel arrangements and mode choices presented in Chapter 6.

4.1 Identification of Joint Household Trips

The general process of identifying joint household trips is presented in Figure 4.1. Unlinked trips are used for the process of identifying joint household travel. A clear contrast between an unlinked trip and a linked trip is that the latter is a journey from one activity to another, excluding change of mode. A linked trip may comprise of one or more unlinked trips. For example, if a person travels from home to work by public transport with a walk trip at either

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2 This chapter is developed from an earlier version of the same, first presented by this author in Ho et al. (2012). Another paper (Ho and Mulley, 2013a) using the dataset described in this chapter has been accepted for publication.
end of the public transport trip, this is one linked trip which comprises of three unlinked trips (walk access, public transport, and walk egress trips).

The reason for using unlinked trips in the dataset as opposed to linked trips is to keep all activity stops, including those to change mode which in turn allows for the identification of joint household travel in any trip of a home-based tour, e.g., joint travel to drop-off or pick-up a household member at a train station. Only fully responding households are chosen for analysis for two reasons. First, this subset of data provides an opportunity to evaluate the performance of a matching criteria method in identifying joint travel. Second, data of a whole household are critical to examining the interdependencies among household members in daily

Figure 4.1 Process of identifying joint household trips from the Sydney HTS data
activity-travel arrangements and travel mode choices. After the exclusion of 715 partially responding households (10%), the three years pooled dataset provided 6,571 households for the identification of joint household trips discussed below.

4.1.1 Data validation and performance measures
The first step was a test on the reliability of reported information by the number of household members participating in a car trip. Therefore, this information is sought in the survey. As the Sydney HTS data were captured for one interviewee at a time, a joint trip by \( n \) household members should ideally be reported consistently by \( n \) household members. A preliminary test based on this principle reveals that only 3 out of 6,571 fully responding households answered a question on the number of car co-travellers inconsistently. These 3 households were discarded from the dataset. Using the information on the number of household members travelling together by car, performance measures are developed to evaluate different sets of matching criteria and identify the best one for the identification of joint household trips. The following performance measures are used with the first two measures being adapted from Shaz and Corpuz (2008).

- Measure 1: the percentage of identifiable household joint drivers.
- Measure 2: the percentage of identifiable household passengers.
- Measure 3: the number of households where members report inconsistent trip details.
- Measure 4: the number of over-identified trips.
- Measure 5: the number of under-identified trips.

These performance measures help understand, manage and improve the effectiveness, efficiency and quality of the matching criteria methods for the purpose of identifying joint household activities and travel. The first two measures indicate the degree to which a process outputs conform to requirements (effectiveness). The third measure suggests the degree to which a set of matching criteria produces the required output at the minimum loss of households in the sample (efficiency). Finally, the last two measures reveal the degree to which the created joint household trip dataset meets the requirements and where improvements can be obtained (quality). The higher the first two measures and the lower the last three measures, the better the matching criteria are in identifying joint household trips and activities.
4.1.2 Matching criteria

To test the best method of identifying joint household travel, including those reported inconsistently by household members, four sets of matching criteria are used 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 four flexibly defined sets of matching criteria all require that joint trips by household members be joint in travel mode, joint in location of trip origin and destination, be made by the same household, and be reported consistently in terms of the number of household members in the car. As the travel party size of non-car trips is not collected by the Sydney HTS, this is recoded as zero so that the matching criteria ignore this condition for non-car trips. Each set of matching criteria additionally applies a joint-in-time condition relating to departure and/or arrival times grouped into 5-minute or 10-minute intervals. It is this joint-in-time condition that distinguishes the four sets of matching criteria. The first and the second sets of criteria relate to both reported departure and arrival times, grouped into 5-minute intervals and 10-minute intervals, respectively; the third set of criteria considers the reported departure time grouped into 10-minute intervals while the fourth set considers the reported arrival time. Applying these four sets of matching criteria to identify joint household trips resulted in four datasets for further evaluation.

4.1.3 Evaluation of matching criteria in identifying joint household trips

As information on the number of household members travelling together is available for car trips only, separate evaluation for car and non-car trips is required. For car trips, an algorithm method is used to test the reliability of information on the number of persons travelling together that is identified by each set of matching criteria. The five performance measures (discussed in Section 4.1.1 above) are used to evaluate and identify the best set of matching criteria.

Table 4.1 shows the performance of the four sets of matching criteria in identifying joint household car trips. The performance measures presented in Table 4.1 are based on car trips alone. Each of the criteria successfully identifies more than 93% and 92% of the expected number of car drivers and car passengers respectively. The more flexible the matching criteria (e.g., with a bigger gap in departure and arrival times), the lower the level of under-identified
joint household trips, but this is found to be at the expense of independent trips being over-identified as joint trips. The joint trip is under-identified if fewer household members are identified to participate in a trip than reported; conversely, if more household members are identified to participate in a trip than reported, the joint trip is over-identified. An example of under-identification is where a joint household trip made by two members is identified as two solo trips. Another example is of a joint trip made by four household members that is identified as two joint household trips, each by two household members.

Table 4.1 Performance of the four sets of matching criteria

<table>
<thead>
<tr>
<th>Matching criteria with a joint-in-time condition using</th>
<th>Measure 1&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Measure 2&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Measure 3&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Measure 4&lt;sup&gt;d&lt;/sup&gt;</th>
<th>Measure 5&lt;sup&gt;e&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1). 5-min intervals, starting &amp; ending</td>
<td>93.2%</td>
<td>92.2%</td>
<td>10.0%</td>
<td>56</td>
<td>1,966</td>
</tr>
<tr>
<td>(2). 10-min intervals, starting &amp; ending</td>
<td>93.9%</td>
<td>92.9%</td>
<td>9.3%</td>
<td>79</td>
<td>1,807</td>
</tr>
<tr>
<td>(3). 10-min intervals, starting</td>
<td>94.8%</td>
<td>93.9%</td>
<td>8.2%</td>
<td>104</td>
<td>1,560</td>
</tr>
<tr>
<td>(4). 10-min intervals, ending</td>
<td>95.1%</td>
<td>93.8%</td>
<td>8.6%</td>
<td>129</td>
<td>1,569</td>
</tr>
</tbody>
</table>

<sup>a</sup> Percentage of identifiable number of household joint driver trips.
<sup>b</sup> Percentage of identifiable number of household passengers.
<sup>c</sup> Percentage of households for which members have reported inconsistent trip details.
<sup>d</sup> Number of joint household trips being over-identified (i.e., more persons than reported travel party size).
<sup>e</sup> Number of joint household trips being under-identified (i.e., fewer persons than reported travel party size).
Total number of person trips is 81,731.

The set of matching criteria (2) is selected as the best set following a trade-off between the performance measures and heavily weighting the ability to avoid over-identified trips since their correction is more difficult. This is because the correction of over-identified trips requires ‘stricter’ matching criteria which will result in a higher number of under-identified trips to be corrected. Although the first set produces a fewer number of over-identified trips, it requires more resources to correct under-identified trips which otherwise results in a loss of the higher percentage of households with inconsistent trip details (see measure 3). A detailed analysis of inconsistent cases which suggests where improvements to the process of identifying joint household travel from the household travel survey data can be obtained. The results of this analysis are reported below, using set (2).

The analysis of inconsistent cases shows departure times were reported more consistently than arrival times. Inconsistent reporting of trip origins and destinations each accounts for about 35% with an overall 30% of inconsistent cases arising from discrepancies in departure and arrival times. This suggests the occurrence of joint household trips and activity episodes is under-identified to a greater extent by matching criteria using a joint-in-location condition at a higher level of detail (e.g., fine travel zone), as compared to those using a more flexible joint-
in-location condition (e.g., local government area). However, matching criteria with a more flexible joint-in-location condition are likely to result in a higher number of over-identified joint household trips/activity episodes by mistakenly classifying different activity locations as the same. This would be important for identifying joint household travel and activity episodes from traditional travel survey data to compare activity locations at an appropriate level of detail.

Segmentation analysis on inconsistent cases revealed trip details by females, non-workers, and children (aged 5 to 14) were reported significantly less consistently in the Sydney HTS (Figure 4.2). Children aged 10 to 14 will usually be completed by personal interview (conducted in the presence of an adult) while children aged 5 to 9 will usually be completed by proxy interview with an adult member of the household. There is no significant correlation between whether a child reported trip details inconsistently and whether a child received help from an adult household member, using a Chi-squared test (p = 0.771). Further, weekend trips were reported significantly less consistently than weekday trips (p < 0.001). This may be explained by the more complex travel patterns of females, non-workers, children and weekend days. Another possible explanation is that trips undertaken by these people and on weekend days are more likely to be discretionary trips, and these trips may be more variable in location as they are not regular and more inconsistently reported as a result.

![Figure 4.2 Percentage of inconsistent trip details by trip maker](image)

*Figure 4.2 Percentage of inconsistent trip details by trip maker*


As mentioned earlier, a separate evaluation method is required for non-car trips where the travel party size is not collected by the Sydney HTS. Applying the best matching criteria for
car trips to non-car trips with the travel party size being ignored, a graphical method is used to identify misidentified joint household non-car trips. By graphically illustrating household members’ travel diaries, the travel party size can be identified which can then be compared by the travel party size identified by the algorithm method (described above). If the two methods provide the same results, the joint household trip is considered as successfully identified. Otherwise, it is mis-identified by the algorithm method because the graphical method is considered more accurate than the algorithm method. The reason is that the graphical method takes into account the connections made between multiple trips and tours taken by each household member and the consistency of travel purposes across all household members.

As the graphical method is manual and expensive in time, it was applied to a 1% ‘randomly’ selected sample of households to recognise the importance of an application to a wider sample. Because graphical validation is intended to focus more on joint household travel by non-car modes, a random sampling frame limits households to those with more than two non-car trips. The random sample included 60 households, 160 persons and 1,093 person trips with 485 walking trips, 396 car trips, 209 public transport trips and 3 trips made by other modes (bicycle and motorcycle).

Figure 4.3 illustrates how joint household travel is identified using an example household with five members. The horizontal axis indicates activity categories; the vertical axis shows time of the day, starting from the 4 am of the start of the travel diary. Each line of a different colour corresponds to the travel of a single household member. Travel mode is denoted by a letter attached to each trip. For example, the continuous red line represents the travel pattern of the wife, who is 42 years old and is a housekeeper. In the morning, she walked her daughter to school, and returned home. At about noon, she walked to a bus stop to catch a bus to a place where she did personal business and returned home by bus. She then walked to school to pick up her daughter at around 3:00 pm. She, her husband and their daughter drove to school to pick up their sons, dropped one son off at his workplace before returning home. At about 6:00 pm, they picked up the son using a car.
Joint household trips in Figure 4.3 are represented by parallel/overlapping lines with the number of parallel/overlapping lines indicating travel party size. Travel mode and travel party size identified by the best set of matching criteria are shown in the bottom right-hand corner box for comparison purposes. For this household, both the graphical method and the matching criteria algorithm provide the same results. Overall, a comparison of the results between the best matching criteria and the graphical method using the 1% random sample of households shows joint walking trips significantly less likely to be under-identified (p = 0.10) and more
likely to be over-identified ($p = 0.08$) than car trips. This may be expected because walking trips are normally short in distance which causes independent trips more likely to have the origins and destinations coded into the same travel zone. In addition, more walking trips are likely to be close in time and the algorithm is unable to distinguish between independent and joint trips which belong to the same 10-minute interval. These two features resulted in a higher level of over-identification for walking trips as compared to motorised trips when trip origin, trip destination, trip starting and ending times allow for differences in reported times to be used as matching criteria. A comparison of the graphical method with the algorithm method using the random sample of households detects no mis-identified trips made by public transport and other modes.

4.2 Correction of Data Inconsistencies

Section 4.1 has described the algorithm and graphical methods that are used to identify joint household trips and data inconsistencies in the Sydney HTS dataset. As shown in Table 4.1, households for which members reported inconsistent trip details account for about 9% of all households in the dataset. This section explains how the data inconsistencies are corrected for the purposes of identifying joint household travel and retaining these households.

In correcting for inconsistencies, three assumptions about joint household trips are made:

1. If two household members jointly travel and there is a difference in trip details, the details reported by the car driver are more reliable than the car passenger;
2. If more than two household members travel together, the trip details consistently reported by the group with the most members are assumed to be the consistent details;
3. If more than two household members travel together and there is no larger group of consistently reported details on trips, the trip details reported by the group including the car driver is assumed to be the consistent details.

‘Inconsistent’ in this context means a difference in the reporting of trip details between/among household members and so ‘inconsistent’ does not necessarily mean ‘incorrect’. A child who travelled jointly with their parents may tend to report exact starting and ending times while the parents reported rounded times; the child is considered as ‘inconsistent’ with the parents even though the child’s reported times may be the correct ones. The lack of ground truth about the travel undertaken by each respondent in the HTS data leads to the use of these assumptions to allow the trip details of the joint travel to be aligned. Whilst the violation of
these assumptions may influence the distribution of data inconsistencies, this does not influence the identification of joint household trips that is the main purpose of this study.

Inconsistent cases are identified by comparing the reported number of household members in the vehicle with the identified number of household members participating in that trip. Inconsistencies are corrected by updating inconsistent records with the values reported by the co-traveller(s) who, according to the assumptions above, are considered consistent. Households for which joint trips were reported by all the participants but the discrepancies could not be reconciled were eliminated from the sample. The best set of matching criteria is applied one more time to the consistent travel diaries to produce the final joint trip dataset. This correction of data inconsistencies substantially improves the performance of the matching criteria in identifying joint household car trips. Specifically, 100% of joint household driver trips become identified and 100% of household passengers are now found. However, the best set of matching criteria still over-estimates a small number of joint household car trips (the same as before) because over-identification can only be corrected with a stricter set of matching criteria. Households with over-identified joint household car trips were eliminated from the sample, as were households with inconsistent trip details that could not be reconciled.

Figure 4.4 shows the number of misidentified joint household trips in the random sample by travel mode before and after correcting data inconsistencies. No under-identified household joint car trips exists in the random sample after correcting data inconsistencies as compared to 14 joint car trips being under-identified before. There is no change to misidentified joint non-car trips before and after the correction of data inconsistencies because only inconsistencies in car trips were corrected. Data inconsistencies in non-car trips can only be corrected manually using the graphical method but this would require attention being given to each individual household in the large sample. Given that joint household travel are made mainly by car and shared rides are more relevant to policy and planning practices than joint walking trips, it is decided to leave misidentified joint non-car trips in the dataset. These misidentified joint trips are likely to be made on foot rather than by public transport as the random sample suggests all public transport trips are correctly identified. Thus, leaving these trips in the data seems to have a minor influence (if any) on the results and their implications for transport policy and planning practices.
Changes to the Sydney HTS dataset through the process of identifying and validating joint household trips are summarised in Figure 4.5. The 3-year pooled Sydney HTS data provided 7,286 households. Of which, 6,568 households are usable with all household members completing the survey and reporting consistent information on the travel party size. These households generated 81,731 person trips with 79,953 person trips (98%) being retained through the process of identifying joint trips and correcting data inconsistencies. The correction of inconsistent trip details has reduced the loss of households with inconsistent trip details from 568 to 84 (6,568 − 6,484 = 84) households.

The identification of joint household trips from the person trip dataset (i.e., travel diaries) creates a new dataset in which each household trip represents a record or row. This household trip dataset comprises of 61,039 records with 13,262 of these being joint trips. These 61,039 household trips are equivalent to 79,953 person trips. A household trip can be either a joint trip between/among household members or a solo trip; a joint trip by two household members, for example, equals two person trips. This new dataset is referred to as the household trip dataset and would be equivalent to data which are captured for one trip/activity at a time, as opposed to one interviewee at a time (i.e. person trip). Apart from the data fields inherited from the travel diaries file, the household trip dataset also includes data fields indicating whether a trip was joint or solo, how many household members were travelling together, who they are (person identifiers) and by what mode the trip was generated. These
data fields were added to the *person trip* dataset to help the identification of joint tour patterns discussed in the next section.

Figure 4.5 Changes to HTS dataset through the process of identifying joint household trips
4.3 Identification of Joint Tour Patterns

If trips are defined as travel with single purpose and single destination, then tours are the scheduling of trips in sequence, beginning at one location and ending at the same location. The individual’s home is usually used as an anchor point and tours are referred to as home-based tours in the literature. A small number of respondents reported travel diaries that began or ended at an out-of-home location, effectively changing the beginning or ending of tours. These tours were discarded from the sample due to a potential difficulty in interpretation. A home-based tour comprises at least one activity stop and two trips: one trip to an activity location and the other to home. Each trip is a member of a unique home-based tour and is referred to as a trip segment hereafter. For tours involving multiple activities/stops (i.e., travel purposes), one of the destinations is considered as the main destination and the travel purpose of visiting the main destination is considered as the main purpose of the entire tour. Tour main purposes are classified into three broad groups based on Stopher et al. (1996) and Bhat and Misra (1999) as follows:

- Subsistence activities are typically frequent activities with fixed location and timing. These activities are essential to providing the finance for pursuing other activities. Subsistence activities are further divided into work/work-related and education with the latter including school and childcare. This is motivated by a growing interest in understanding school travel patterns and distinct population segments undertaking work tours vs. education tours;

- Maintenance activities are activities undertaken on a regular basis but with variable timing and location. Activities clustered into this group include shopping, personal business/services including medical/dental visits, and serve passenger (accompanying or dropping off/picking up someone);

- Discretionary activities are performed on an irregular basis with variable locations and timing. These activities are mainly social and recreational activities motivated by cultural and psychological needs.

A home-based tour may involve multiple travel modes. Consistent with the literature, this study assumes that for tours involving multiple modes, not all modes are the main ones for the tour. Rather, a hierarchy is adopted to identify a tour’s main travel mode using the following priority order:

- Public transport (including train, bus, ferry, light rail, and taxi);
- Car (including car driver and car passenger);
- Walking
The reason for this ordering is that the higher priority modes are more likely to take up the longest part of the tour, especially in time, and would be a controlling factor for the person arranging their travel (BTS, 2011a). Another reason is that lower priority modes can be considered as ‘feeder’ modes (Currie and Delbosc, 2011). Travel modes such as bicycle and wheelchair are not considered because of their rarity in the empirical data (less than 0.5% of tours).

In this study, a tour is considered to be joint if any trip segment is made jointly with one or more household members. Household members travelling together may have the same or different travel purposes. When the participants’ travel purposes are the same, joint travel is usually followed by a joint engagement in the activity at the destination. When the travel purposes are different, the activities at the destination are considered independent with a shared ride. Without participating jointly in the activity, shared rides are still recognised as being part of the joint decision making process as they imply an agreed upon time and space constraint between/among household members in their daily travel arrangements.

The *person trip* dataset (i.e. travel diaries) with fields indicating how many and with whom the respondent was travelling is restructured to create a new dataset in which each home-based tour represents a record (i.e. row). The creation of a *home-based tour* dataset enables the identification of joint tour patterns through the identification of joint household trip segments that comprise all or part of a home-based tour. In the home-based tour dataset, each home-based tour makes up a record (i.e. row) and attributes of each and all trip segments made up that tour are stored in separate fields (i.e. columns). The structure of the home-based tour data therefore increases substantially (*n* = 39 times where *n* is the maximum number of trip segments in home-based tours) after restructuring the *person trip* dataset. The home-based tour dataset includes attributes at the tour level such as the tour’s main purpose and the tour’s main mode. These are identified from the travel purposes and the travel modes of all trip segments chained into a tour using the priority lists discussed above. The home-based tour dataset also includes the number of trip segments chained into a tour, the number of household members relevant to the tour and their person identifiers. These data fields help in differentiating joint tour patterns discussed below.

Joint travel between/among household members can occur in any trip segment of a home-based tour, and it can be at the second trip segment on a home-based tour of one household member but at the fourth, fifth or last trip segment on the home-based tours of other
household members. Different sets of conditions are developed to deal with this complexity of joint household tour patterns. Generally, joint tour patterns are identified by linking and matching relevant trip segments of each household member’s home-based tour using a unique home-based tour identifier. This study identifies nine joint patterns of intra-tour coordination between/among household members in the dataset:

- Fully joint tour (tour type J1);
- Shared rides to an activity location from home (drop-off, tour type J2);
- Shared rides to home from an activity location (pick-up, tour type J3);
- Shared rides to and from an activity location (shared rides, tour type J4);
- Fully joint tour and shared rides to an activity (joint & drop-off, tour type J5);
- Fully joint tour and shared rides to home (joint & pick-up, tour type J6);
- Fully joint tour and shared rides to and from an activity (joint & shared rides, tour type J7);
- Shared rides in the middle of a tour (joint in middle tour, tour type J8);
- Individual tour (tour type J9).

These nine joint tour patterns, representing nine different ways of arranging household activities and travel into a home-based tour, are discussed through the nine examples that follow. Figure 4.6 through Figure 4.14 show how household members interact on all or part of their home-based tours in each case. The classification, described here, extends 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. More specifically, this study focuses on joint household travel arrangements and identifies joint tour patterns from joint trips chained into a tour. This is in contrast to the study of Gliebe and Koppelman (2005) which identifies joint tour patterns based on activities undertaken at the destination (i.e., whether these activities are shared or independent).

**Fully joint tour (J1):** Figure 4.6 illustrates a fully joint tour in which two household members travel together on all trip segments of a tour. This pattern may include single or multiple activity stops with joint travel in between. Typically, this tour pattern involves joint participation of household members in a joint activity such as recreation at the destination. However, this pattern type also includes cases in which household members travel together without participating jointly in any activity. For example, a husband drives his wife to a shopping centre, waits outside and drives her back to home without participating jointly in the shopping activity. Another example is normally referred to as ‘soccer mom’ and ‘taxi dad’
when a parent jointly travels with their child on all trip segments of a home-based tour but does not participate physically to the activity. Despite differences in basis for identifying joint tours, this fully joint tour pattern is likely to be identical to that described by Gliebe and Koppelman (2005).

Figure 4.6 A fully joint tour pattern (J1)

Drop-off tour (J2): Figure 4.7 shows a joint tour pattern in which two household members share rides to an activity location, then go their separate ways and return home separately. This study does not differentiate between who serves and who is being served to focus on the fact that a shared ride has been agreed upon by the participating household members. This tour pattern includes cases in which one or both persons head directly home or go to other activities before returning home. An important consideration is that this pattern does not include a shared ride home. An example is that a parent drops their child off at the school on the way to work; the child then travels on their own to home using public transport or walking while the parent may go grocery shopping on the way from work to home.

Figure 4.7 A tour pattern with a shared ride from home or drop-off (J2)

Pick-up tour (J3): Figure 4.8 portrays a joint tour pattern in which two household members meet at an out-of-home activity location and return home together. At least one of the two persons pursues independent activities before the meeting, such that an out-of-home meeting is necessary. They may head home directly or may participate in a joint activity before returning home. An example is that a parent picks up a child at school on the way from work to home while they leave home separately. Another example is that a wife after doing personal business joins in grocery shopping with her spouse and they return home together.
Shared ride tour (J4): This joint tour pattern is a combination of the second and the third patterns. Figure 4.9 illustrates an example in which a child is dropped off by the father on the way to his work and is picked-up by the mother after school. The mother and the child may engage in an activity jointly before returning home together. In this example, the child shares both rides in the same tour but with different household members. This tour type pattern also includes cases in which the person receiving the ride experiences both rides in the same tour with the same household member who may undertake both drop-off and pick-up in one tour, or may return home in between the rides, forming two separate tours. An important element is that at least one household member experiences both rides in the same tour.

Fully joint and drop-off pattern (J5): This joint tour pattern is a combination of the first and the second patterns. Figure 4.10 depicts a travel arrangement in which two household members jointly drop-off a third member at an activity site or a train station. After giving rides, they may engage in a shared activity or return home directly. All participants to this tour pattern start their tours together, but at least one person leaves the others before they all return to home.
Fully joint and pick-up pattern (J6): This joint tour pattern is a combination of the first and the third patterns (J1 and J3). Figure 4.11 illustrates a travel arrangement of three household members 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. This joint tour pattern may include one or more joint activities by all three household members before returning home. All participants to this tour pattern end their home-based tours together, but not all participants start the tour jointly. For instance, parents and their children leave home separately but in pairs, each pair engages in activities jointly and meets the other pair for another joint activity and/or a shared ride to home. In some cases, the children arrive by public transport or receive a ride from the third party while the parents use a household car and drive them all home.

Fully joint and shared rides pattern (J7): Figure 4.12 illustrates a joint tour pattern in which a household member is dropped off and picked up by other household members. The person who gives rides may complete both drop-off and pick-up in the same tour, or they may return home in between the rides, forming two separate tours. This tour type pattern is a combination of the first and the fourth patterns (J1 and J4). Typically, all participants leave home together, but at least one household member engages in an independent out-of-home activity prior to
the meeting, such that an out-of-home meeting and a shared ride to home is necessary, and at least two household members travel jointly to all activity stops, such that a fully joint tour is formed.

![Figure 4.12 A fully joint tour pattern with shared rides (fully joint & shared rides, J7)](image)

*Shared rides in the middle of the home-based tour (J8):* Figure 4.13 depicts 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. This is a relatively infrequent pattern found in complex and multiple destination tours. An example is that a household member after work picks up another member at their workplace; they go for dinner together but resume their independent activities afterward, such that separate travel home is necessary. All participants in this tour pattern start their tours separately, such that an out-of-home meeting for a joint activity or a shared ride is necessary, and at least one person engages in an independent activity after the meeting, such that separate travel home is necessary.

![Figure 4.13 A joint tour pattern with shares rides in the middle (J8)](image)

*Individual tour (J9):* An individual tour is a tour pattern without any full or partial joint travel with any other household members as illustrated in Figure 4.14. It should be noted that individual travel does not necessarily mean no interactions between household members. For instance, a husband does grocery shopping after work while the wife picks up their children at the school; even though the couple travel independently, their decisions about travel patterns may not be independent of each other.
Table 4.2 shows the occurrence of the nine joint tour patterns using the Sydney 3-years pooled HTS data. Fully joint tour pattern (J1) accounts for over a quarter of all home-based tours in the sample. In contrast, joint in the middle tour pattern (J8) accounts for only 1% with 155 tours out of 23,017 home-based tours in total. Complex joint tour patterns with a combination of a fully joint and a shared ride (J5, J6, and J7) are also less frequent with each tour pattern accounting for about 2% to 3% of the total tours. Individual tours are most prevalent and represent 45% of the total home-based tours.

Table 4.2 Frequencies of joint tour patterns in Sydney

<table>
<thead>
<tr>
<th>Tour pattern</th>
<th>Frequency</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully joint tour (J1)</td>
<td>6,387</td>
<td>28%</td>
</tr>
<tr>
<td>Drop-off tour (J2)</td>
<td>1,499</td>
<td>7%</td>
</tr>
<tr>
<td>Pick-up tour (J3)</td>
<td>1,246</td>
<td>5%</td>
</tr>
<tr>
<td>Shared rides (J4)</td>
<td>1,623</td>
<td>7%</td>
</tr>
<tr>
<td>Fully joint and drop-off (J5)</td>
<td>536</td>
<td>2%</td>
</tr>
<tr>
<td>Fully joint and pick-up (J6)</td>
<td>562</td>
<td>2%</td>
</tr>
<tr>
<td>Fully joint and shared rides (J7)</td>
<td>589</td>
<td>3%</td>
</tr>
<tr>
<td>Joint in middle tour (J8)</td>
<td>155</td>
<td>1%</td>
</tr>
<tr>
<td>Individual tour (J9)</td>
<td>10,419</td>
<td>45%</td>
</tr>
<tr>
<td>Total home-based tours</td>
<td>23,017</td>
<td>100%</td>
</tr>
</tbody>
</table>


The nine joint tour patterns discussed above can be extended to match the travel party size and other components such as activity type (shared activity vs. individual activity) and tour complexity. For example, while only two lines (two persons) are used in the fully joint pattern...
(J1) for illustration purposes, this tour pattern can be split according to the travel party size of two, three, four or more people depending on the rates of occurrence in the empirical data and the study purposes (e.g., to investigate the modal shift due to the implementation of high occupancy vehicle vs. high occupancy toll lanes). Similarly, the systematic typology of joint tours is able to distinguish drop-off (J2) and pick-up (J3) tour patterns from joint outbound and joint inbound half-tours by considering the number of trip segments chained into a tour and comparing the location where a drop-off/pick-up occurs with that of the tour’s main destination. This is discussed further in Chapter 5 where the empirical data are analysed and descriptive statistics are presented.

The identification of the nine joint tour patterns is straightforward given the set of conditions applied for each joint tour pattern discussed above and the home-based tour dataset with data fields indicating the number and the travel party size of all trip segments chained into a tour. The number of trip segments helps identify the last trip segment of each home-based tour and the travel party size distinguishes solo trips from joint trips chained into a tour. The trip type (solo vs. joint) and the number of trip segments chained into a tour are used to define the set of conditions that matches with each of the nine joint tour patterns. The process of identifying joint household tour patterns is summarised in Figure 4.15. This process is automatically executed by an algorithm written in SPSS syntax.
4.4 Summary of Research Data

This chapter has described the steps taken to transform the 3-year pooled Sydney HTS data (2007/08, 2008/09 and 2009/10) into the home-based joint tour dataset that is used for the analysis of joint household travel arrangements and travel mode choices. Intra-household joint tour patterns are identified in two stages. The first stage is to identify joint household trips from unlinked person trip dataset, adapting the flexibly defined matching criteria method.
developed by Kang and Scott (2011). The reported number of household members travelling together 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.

The process of identifying joint household travel has created two additional datasets from the original travel diaries or person trip dataset. The created datasets are household trip and home-based tour. A clear contrast amongst these three datasets is the unit of analysis that a record/row in each dataset represents. In the original travel diaries collected by the Sydney HTS, each record represents a person trip and therefore is the name of this dataset. In the household trip dataset, each record represents a household trip which can be either solo or joint. A joint household trip by three household members, for example, is recorded as one trip in the household trip dataset, in contrast to three trips in the person trip dataset. In the home-based tour dataset, each record represents a home-based tour which is a sequence of trips starting and ending at the home. Most trip-based analysis including those reported by BTS uses the person trip as the unit of analysis. However, in this study the household trip is used to produce trip-based statistics unless otherwise indicated. Household car trips are more relevant to traffic congestion and corresponding policy than person trips as the former reflect the real number of cars on the road while the latter needs an average car occupancy ratio to convert.

In terms of attribute, the home-based tour and household trip datasets are richer than the person trip dataset. Compared to the person trip dataset, the household trip dataset includes additional data fields indicating the trip status (joint vs. solo), the travel party size and person identifiers of all participants which can be linked to the person dataset (described in Chapter 3) to have more information on the travel party composition. The home-based tour dataset comprises of attributes at the tour level including joint tour type, tour’s main purpose and main mode, person identifiers of all household members relevant to the tour, and the number of trip segments chained into a tour. The home-based tour dataset also includes trip attributes of each trip segment chained into a tour.

This chapter has developed a systematic typology of joint home-based tours which helps in differentiating tours based on tour structure and the implied intra-household interactions. For the sake of convenience, the nine joint tour patterns are brought together and presented in Figure 4.16. The typology of joint tours can be extended to match other components of tour
such as the travel party size, the activity type and tour complexity, depending on the study purposes and the rates of occurrence of different joint tour types in the empirical data. This is the subject of the next chapter which provides a descriptive analysis of joint household travel using the datasets constructed in this chapter.
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.

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

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.

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

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.

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.

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.

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 4.16 Typology of joint home-based tours
CHAPTER 5. DESCRIPTIVE ANALYSIS

Chapter 3 and Chapter 4 have described the Sydney HTS data and the steps taken to transform this original dataset into the joint household tour and joint household trip datasets used for testing the research hypotheses identified in Chapter 2. This chapter provides a descriptive analysis of joint household travel as a precursor to modelling intra-household interactions in travel mode choices. The descriptive analysis performed in this chapter partially addresses the first two hypotheses regarding the relevance of joint household travel to individual’s choice of travel mode and the roles of household resources and the household’s spatial setting in motivating/constraining joint household travel arrangements. Another objective of this chapter is to identify important explanatory variables for the development of empirical models in Chapter 6 to fully consider the hypotheses outlined in Chapter 2.

Chapter 2 has identified a number of studies enumerating joint household activity and travel in the literature. However, these studies used different units of analysis which have constrained the extent to which their results can be compared. A main motivation of this chapter is draw a more general picture of joint household travel across countries as the way to inform the importance of modelling intra-household interactions in daily activity-travel behaviour. It does this by using the Sydney GMA as the case study and using different units of analysis employed in the literature, and then comparing the results across studies. This chapter first describes the share of joint household travel with trip, tour, and daily activity-travel pattern being treated as the units of analysis. This is followed by a deeper analysis on the home-based tour dataset and a comparison of weekday and weekend joint household activities and travel. The tour-based analysis first provides a general comparison of activity participation and mode of travel across weekdays and weekends before turning to an investigation of joint household travel arrangements in which choices of joint tour patterns and mode of travel are analysed by various dimensions. The dimensions include travel purposes, activity types, tour complexity, travel party composition, household and individual characteristics. The chapter ends with a discussion on the implications for modelling joint household travel arrangements and mode choices.

5.1 Joint Household Travel and Unit of Analysis

Different units of analysis produce different percentages of joint household travel and this has constrained the extent to which results from previous studies have been compared in order to draw a general picture of joint household travel across countries. In doing so, this section uses
three units of analysis including trip, home-based tour, and daily activity-travel pattern (DAP). The household trip and home-based tour datasets constructed in Chapter 4 are used. No sampling weights are used in the descriptive analysis or in the model estimation. The results are compared with those from other studies that use a comparable unit of analysis. Data from Halle and Karsruhe in Germany are taken from Shighi (2001) where the trip was used as the unit of analysis. Data from Mid-Ohio in the US are taken from Vovsha et al. (2003) where the home-based tour was used as the unit of analysis. Joint household activities and travel in Washington D.C. are obtained from Gliebe and Koppelman (2005) who used the daily activity-travel pattern as the unit of analysis. Although these studies may not provide a direct comparison to the data in Sydney due to different units of analysis and research focuses, they still provide indicative comparisons for this study.

Table 5.1 provides the distribution of household trips in Sydney by trip status with joint household trips being extended to match with the travel party size (the number of household members travelling together). In Sydney, for an average day, 22% of all trips are made jointly by household members, of which about three quarters are by two household members. The proportion of joint household trips is much higher on weekends (32%) than on weekdays (19%). Singhi (2001) reported a similar percentage of joint household trips on an average day in two German cities, Halle and Karsruhe. Even though the study by Singhi (2001) had a total number of observations (i.e. household trips) comparable with the current study, the number of households sampled was small (139 households with 317 persons over 6 weeks). The Sydney study has the advantage of a larger sample size which potentially provides a more accurate and representative measure of joint household travel at a regional level.

Table 5.1 Distribution of household trips by trip status, Sydney 2007 – 2010

<table>
<thead>
<tr>
<th>Trip type</th>
<th>Average day</th>
<th>Average weekday</th>
<th>Average weekend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solo trip</td>
<td>78%</td>
<td>81%</td>
<td>68%</td>
</tr>
<tr>
<td>Joint trip</td>
<td>22%</td>
<td>19%</td>
<td>32%</td>
</tr>
<tr>
<td>by 2 persons</td>
<td>15%</td>
<td>13%</td>
<td>22%</td>
</tr>
<tr>
<td>by 3 persons</td>
<td>4%</td>
<td>4%</td>
<td>6%</td>
</tr>
<tr>
<td>by 4 persons</td>
<td>2%</td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td>by 5 persons</td>
<td>0%</td>
<td>0%</td>
<td>1%</td>
</tr>
<tr>
<td>by 6 persons</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>by 7 persons</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Total household trips | 61,039 | 47,496 | 13,543 |

Table 5.2 shows the distribution of joint household travel in Sydney with the home-based tour being used as the unit of analysis. Home-based tours are classified using the typology of joint tours developed in Chapter 4. Joint household travel, either fully or partially, accounts for more than half of the total home-based tours on an average day in Sydney, compared to 22% when the trip is used as the unit of analysis. As with the trip-based analysis, the tour-based analysis shows a larger percentage of joint household travel on weekends (61%) than on weekdays (52%). Vovsha et al. (2003) reported a comparable percentage of joint home-based tours on an average weekday in Mid-Ohio and New York cities in the USA but did not investigate weekend travel.

Table 5.2 Distribution of home-based tour by joint tour type, Sydney 2007 – 2010

<table>
<thead>
<tr>
<th>Tour type</th>
<th>Average day</th>
<th>Average weekday</th>
<th>Average weekend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual tour (J9)</td>
<td>45%</td>
<td>48%</td>
<td>39%</td>
</tr>
<tr>
<td>Fully joint tour (J1)</td>
<td>28%</td>
<td>21%</td>
<td>46%</td>
</tr>
<tr>
<td>Drop-off tour (J2)</td>
<td>7%</td>
<td>8%</td>
<td>3%</td>
</tr>
<tr>
<td>Pick-up tour (J3)</td>
<td>5%</td>
<td>6%</td>
<td>3%</td>
</tr>
<tr>
<td>Shared rides (J4)</td>
<td>7%</td>
<td>8%</td>
<td>3%</td>
</tr>
<tr>
<td>Fully joint and drop-off (J5)</td>
<td>2%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>Fully joint and pick-up (J6)</td>
<td>2%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>Fully joint and shared rides (J7)</td>
<td>3%</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td>Joint in middle tour (J8)</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Total home-based tours</td>
<td>23,017</td>
<td>16,522</td>
<td>6,495</td>
</tr>
</tbody>
</table>


The individual daily activity-travel pattern (DAP) is another unit of analysis that has been used in the literature for analysing intra-household interactions. An individual DAP dataset is created from the home-based tour dataset by linking individual tours in sequence, creating a new dataset in which each record represents an individual’s daily travel. Put simply, if a tour is a sequence of trips then a DAP is a sequence of tours undertaken on a day. An individual DAP is considered to be joint if it includes any joint tour. This is consistent with the definition used in Gliebe and Koppelman (2005) to which the results are compared. Creating the DAP dataset reduces the sample size to the extent that a single DAP involves more than one home-based tours. Table 5.3 shows the distribution of individual DAPs in Sydney. Individuals who made no travel or stayed home all day on the survey day are included in the DAP dataset to make it comparable with the study of Gliebe and Koppelman (2005). Daily activity patterns that involve joint household travel accounts for 50% of total individual DAPs on an average day with weekends being more likely than weekdays to involve joint DAPs. This distribution
between weekdays and weekends is consistent with the tour-based and trip-based analysis presented above.

Table 5.3 Distribution of individual daily activity patterns, Sydney 2007 – 2010

<table>
<thead>
<tr>
<th>DAP type</th>
<th>Average day</th>
<th>Average weekday</th>
<th>Average weekend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint</td>
<td>50%</td>
<td>48%</td>
<td>54%</td>
</tr>
<tr>
<td>Independent</td>
<td>34%</td>
<td>37%</td>
<td>24%</td>
</tr>
<tr>
<td>At home all day</td>
<td>17%</td>
<td>15%</td>
<td>22%</td>
</tr>
<tr>
<td>Total individual DAPs</td>
<td>18,330</td>
<td>13,087</td>
<td>5,243</td>
</tr>
</tbody>
</table>


Figure 5.1 compares joint household travel across countries using the three units of analysis discussed above. In Figure 5.1, percentages of joint household trips are for an average day while percentages of joint tours and joint DAPs are for an average weekday. This is to control for the effect of weekday and weekend on the difference in joint household travel between Australia and other countries as the German dataset includes all days of the week while the USA datasets involve weekdays only (Axhausen et al., 2002; Vovsha et al., 2003; Gliebe and Koppelman, 2005). Figure 5.1 shows an almost-identical distribution of joint household trips between Australia and Germany. In terms of tours, there is a small difference in the proportion of fully joint tours between Sydney and Mid-Ohio but the differences become larger for drop-off, pick-up and mixed tours. Moreover, while drop-off and pick-up tours account for a larger proportion in Mid-Ohio than in Sydney, the reverse is true for mixed joint tour patterns (i.e. shared rides, fully joint and drop-off, fully joint and pick-up, fully joint and shared rides, and joint in middle tours). This is probably for two reasons. First, there is a difference between the Sydney and the Mid-Ohio samples with the latter including motorised tours only (Vovsha et al. 2003). Second, drop-off and pick-up tours are more likely to be made by motorised modes than non-motorised modes while mixed tours on weekdays are dominated by school travel which is fairly localised and often made on foot. Together, these suggest that drop-off and pick-up tours might be over-represented whereas mixed tours are under-represented in the Mid-Ohio sample. As for DAP, there is a large difference in the proportion of joint DAP between this study and the one in Washington, D.C. which can be explained by the data in this Sydney case study being for all household members while those from Washington, D.C. are only for the two household heads.
The comparison presented in Figure 5.1 shows a number of similarities in travel behaviour internationally but it also highlights a noticeable difference in the proportion of joint household travel when different units of analysis are used. In terms of trips, joint household travel accounts for about 22% of total travel but this percentage increases to about 50% when the unit of analysis is a tour. Analysing tours, as opposed to unlinked trips, can provide a better understanding of travel behaviour and a more appropriate framework for examining responses to transport polices. For instance, the scheduling of so-called ‘discretionary’ activities during peak hours appears illogical in the context of unlinked trips but is perfectly understandable with tour-based analyses because these non-work activities are frequently linked to commutes (Strathman and Dueker, 1995). Also, the need to satisfy non-work obligations in commuting journeys could explain the findings elsewhere of workers’ reluctance to rescheduling their commutes (Small, 1982; Wilson, 1989).

### 5.2 Tour-based Analysis

This section provides a deeper analysis of joint household travel using the *home-based tour* dataset. The section first presents activity participation rates and mode shares by main activity in Sydney. The joint tour types described in Section 4.3 are analysed by the tour’s main purpose, activity type (shared vs. independent), individual and household characteristics. The choice of travel mode for different joint tour patterns are also analysed by various dimensions.
including travel party composition, household car ownership, the household’s spatial setting, and tour complexity. This is to draw implications for modelling the influence of joint household travel arrangements in which intra-household interactions are implicit on individual travel mode choices.

5.2.1 Activity participation and mode of travel

Figure 5.2 presents activity participation rates and mode shares by tour’s 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 5.2 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%). Also, there is a large difference in sample size between weekday and weekend datasets with almost three times of tours on weekday compared to weekend (16,522 vs. 6,495 home-based tours).

The bar chart in Figure 5.2 compares modal shares across weekdays and weekends, segmented by travel purpose. Overall, public transport (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 5.2 demonstrates that it is the activity distribution which appears to be driving the differences in modal share between weekdays and weekends with work and education being the main segments of public transport use but weekend travel is mostly non-work, non-education based, and so the public transport share is much lower on weekends. In addition, Chi-squared tests suggest statistical differences in modal share between weekday and weekend travel, given the main activity type (p-values for work, education, maintenance and discretionary activities are 0.001, 0.898, 0.012, and 0.001). The insignificant difference in modal share for education tours between weekdays and weekends may be due to the small sample size on weekends.
5.2.2 Distribution of home-based tours by joint tour type

Figure 5.3 shows the distribution of joint household tour patterns (summarised in Figure 4.16) by tour main purpose for an average weekday in Sydney. For all purposes combined, the weekday sample includes 16,522 home-based tours with 48% of these tours being made by individuals. Tours involving joint household travel thus accounts for more than half of the total weekday tours in Sydney with fully joint tours (J1) representing the most important joint tour type (21%), equal to all partially joint tours (J2, J3, and J4) taken together (22%).

Figure 5.3 shows that joint household travel (including fully joint, partially joint and mixed tours) are high for the three combined purposes of education (school and childcare), maintenance, and discretionary. In contrast, tours to work or work-related business are mostly individual but partially joint tours also account for a substantial proportion (20%). While maintenance and discretionary tours have a substantial share of fully joint travel, education tours are characterised by a high share of partially joint travel. The latter can be explained by the fact that joint travel to education is not normally followed by a joint activity, and that school and other activities such as work and serving passenger are often only synchronised for one direction (Vovsha et al., 2003). Furthermore, the fully joint and shared rides pattern (J7) accounts for a high portion of education tours indicating the existence of interpersonal constraints and interactions in daily activity and travel. For example, an interpersonal constraint would be that an infant, who would not be left at home alone, accompanies their mother as she is driving their sibling to school. Another example is that two students, studying at the same school, are being dropped off and picked up on a same car tour.

In Figure 5.3, the systematic typology of tours is extended to match the travel party size for the fully joint tour type (J1). This can also be done for the mixed tour patterns (J5 – J7) but the empirical data show only a small proportion of mixed tours with four or more household members involved. Similarly, although the typology of the tour is able to distinguish drop-off (J2) and pick-up (J3) tour patterns from joint half-tours, these tours are not split because of their infrequent occurrence in this empirical dataset. Only 5% of drop-off tours shown in Figure 5.3 can be classified as joint outbound half-tours where a drop-off occurs at the same location as the tour's main destination. In 70% of the cases defined as drop-off tours, joint outbound half-tours and drop-off tours are identical. In other words, they are different only in name because these tours contain only two trip segments. The remaining 25% of tours are drop-off tours where a drop-off occurs at a location that is different from the main destination of the entire tour. Similar proportions are observed for joint inbound half-tours and pick-up tours.

Figure 5.4 compares weekday with weekend joint household travel in Sydney. It can be seen that fully joint tours (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) are to a lesser extent more prevalent on weekdays (8%) than on weekends (5%). As with weekday travel, weekend joint household travel is mainly for
maintenance and discretionary activities. However, holding activity type constant, weekend and weekday joint tour patterns are significantly different, especially for maintenance and discretionary activities using Chi-square tests (p < 0.001). 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 arrangements.

Figure 5.4 Distribution of joint household tours in Sydney: weekday vs. weekend

5.2.3 Shared activities on joint tours

The tendency of chaining shared activities into a joint tour pattern is investigated in this section. Table 5.4 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 proportion of shared activities chained into partially joint tours (J2 – J4) may be higher than expected as these tour patterns include...
joint half-tours. 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 is 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 and their duration will include school time. This is reinforced by the very short median duration of shared activities chained into the same joint tour type on weekends when school activities are not in place.
Table 5.4 Shared activities chained into joint tours: occurrence, duration, and difference between weekday and weekend

<table>
<thead>
<tr>
<th>Fully Joint J1(2)</th>
<th>Fully Joint J1(3)</th>
<th>Fully Joint J1(4*)</th>
<th>Drop off J2</th>
<th>Pick up J3</th>
<th>Shared rides J4</th>
<th>Joint &amp; Drop J5</th>
<th>Joint &amp; Pick J6</th>
<th>Joint &amp; Shared J7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average occurrence of shared activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weekday</td>
<td>67%</td>
<td>44%</td>
<td>45%</td>
<td>10%</td>
<td>17%</td>
<td>24%</td>
<td>87%</td>
<td>89%</td>
</tr>
<tr>
<td>Weekend</td>
<td>80%</td>
<td>53%</td>
<td>63%</td>
<td>16%</td>
<td>26%</td>
<td>34%</td>
<td>90%</td>
<td>85%</td>
</tr>
<tr>
<td>p-value †</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.005</td>
<td>0.001</td>
<td>0.000</td>
<td>0.205</td>
<td>0.138</td>
</tr>
</tbody>
</table>

| Median duration of shared activities (minutes) |
| Weekday          | 75                | 75                | 95           | 10          | 24             | 17              | 13              | 15              | 325             |
| Weekend          | 75                | 88                | 122          | 65          | 58             | 48              | 48              | 50              | 13              |
| p-value †*       | 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              |

† Differences in average occurrence rates between weekday and weekend are tested with independent samples t-test; * Differences in median durations of shared activities are tested with the nonparametric median test.


5.2.4 Mode of travel by joint tour type

Figure 5.5 shows the difference in modal shares for all joint tour types compared to individual tours (J9). 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 5.5 shows that the car share increases significantly if tours involve either fully or partially joint travel, and that the more complex the joint 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). The economic benefits of using a household car for tours involving fully joint travel may explain the increased car share of these tours. In contrast, a higher share of PT mode for tours involving drop-off and/or pick-up (J2 and J4) compared to individual tours reflects the need of joint household travel arrangements to/from PT nodes under household resource, time, and space constraints. This is discussed further in the next section which looks at the role of household resources and the household’s spatial setting on PT use.
Figure 5.5 Difference in modal share for joint tours as compared to individual tours, average weekday in Sydney 2007 – 2010


Figure 5.6 compares weekend with weekday modal shares by joint tour type with the fully joint tour (J1) being extended to match with the number of participants. 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 tours 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 Figure 5.4) 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 5.6 also shows that travel mode shares split differently across joint tour patterns, after controlling for the effect of weekdays and weekends. The more complex the joint activity-travel pattern, the more likely the car mode is used with fully joint tours (J1) being less likely than partially joint tours (J2, J3, and J4) to involve public transport use. This suggests that public transport is not as suitable for joint household travel and is more likely to require drop-off/pick-up at either end of the tour.
5.2.5 Joint travel arrangements: effect of household resources and spatial setting

This section aims to explore the role of household resources and the household’s spatial setting on joint household travel arrangements. Weekday travel is presented first as intra-household shared ride arrangements (i.e. drop-off and pick-up) are more prevalent on weekdays than on weekends (see Figure 5.4). A discussion on weekends follows which explains as to why descriptive analysis on weekend is not helpful.

Figure 5.7 compares modal shares by joint tour type across households with different levels of car availability, defined in this study as car-sufficient, car-negotiating, and no-car households. Car-negotiating households are households with fewer cars than licence holders (drivers) and car-sufficient households are households with at least as many cars in the household as licence holders. Overall, households with a lower level of car availability use PT more and walk more. Modal shares differ significantly between no-car households and car-owning households but less so between car-negotiating households and car-sufficient households. However, car-negotiating households walk significantly more than car-sufficient households for joint tour patterns J5 and J6 of which a typical example is that mothers with an infant walk their sibling to/from school.

Data source: Sydney HTS 2007 - 2010.

* Differences in modal shares between weekdays and weekends are not significant at the 5% level, using the Chi-square test.

Figure 5.6 Tour-based mode share by joint tour type, Sydney 2007 – 2010

Holding household car ownership constant, fully joint tours are less likely than partially joint tours to be made by PT, although this is less true for no-car households who are captive users of PT. This finding suggests that PT is not as suitable for fully joint household travel which requires drop-offs and/or pick-ups at either end of the tour. This would be to some extent explained by the role of intra-household interactions under household resource constraints (e.g. the household car needs to be back home for a housekeeper 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.

Intra-household interactions in PT use are explored by comparing individual tours (J9) with tours involving joint travel at either end (J2, J3, and J4) in terms of access mode and access distance. In terms of terminology, individual PT tours which have car access at each end are referred to as Park and Ride (P&R) to contrast with those PT tours with drop-off/pick-up being made by car being referred to as Kiss and Ride (K&R). Table 5.5 shows that three-quarters of individual PT tours are accessed by walk while 64% of PT tours involving joint travel at either end are K&R (most of these K&R tours have joint travel on the car leg with
only few cases being followed by a joint PT leg). Also, the differences in median walking access distance between PT tours with and without drop-off/pick-up are insignificant, suggesting that the spatial separation between home and PT nodes is not a factor motivating intra-household interactions in PT use with walk access and that a motivation could be inferred as companionship. For PT tours with car access, P&R had a far longer access distance than K&R. This may be the result of inter-personal constraints which lead to a shorter access distance for K&R (e.g. a car commuter en route to work drops off his partner at a train station closer to home than her most desired station which otherwise detours to his journey). Similarly, temporal and spatial constraints may make K&R less attractive economically than P&R, resulting in observing a longer access distance for P&R.

Table 5.5 Access distance (in km) by access mode and joint tour type

<table>
<thead>
<tr>
<th>Access mode and joint tour type</th>
<th>Individual PT tours, accessed by PT tours with drop-off/pick-up by</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Walking</td>
</tr>
<tr>
<td>Median</td>
<td>0.65</td>
</tr>
<tr>
<td>75 percentiles</td>
<td>1.03</td>
</tr>
<tr>
<td>Sample</td>
<td>1,136</td>
</tr>
<tr>
<td>Access mode share</td>
<td>74.7%</td>
</tr>
</tbody>
</table>

*Total shares do not equal 100% because access trips shorter than 100m are not recorded by the Sydney HTS.


Households with different resource constraints may interact differently in the allocation of household resources and the arrangement of joint household travel in the form of drop-off and pick-up. Table 5.6 compares the median car access distance of car-negotiating households with that of car-sufficient households for PT tours accessed by car. For PT tours with P&R, there is no statistical difference between car-negotiating and car-sufficient households. However, for 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 accessed by P&R if the traveller holds 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 5.6 Median car access distance (in km) by household car ownership

<table>
<thead>
<tr>
<th>Access distance in km</th>
<th>PT tours with P&amp;R</th>
<th>PT tours with K&amp;R</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Car-negotiating</td>
<td>Car-sufficient</td>
</tr>
<tr>
<td>Median</td>
<td>5.05</td>
<td>2.72</td>
</tr>
<tr>
<td>Sample</td>
<td>56</td>
<td>193</td>
</tr>
<tr>
<td>Significant level*</td>
<td>p = 0.542</td>
<td>p = 0.050</td>
</tr>
</tbody>
</table>

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


The efficient use of limited household resources is another factor which could motivate intra-household interactions in PT use as ceteris paribus, car-negotiating households are found to be more likely than car-sufficient households to make K&R (77% vs. 58%) given a PT tour with car access. This is further reinforced when considering the licence status of K&R users. K&R users from car-negotiating households are more likely than those from car-sufficient households to be licence holders (65% vs. 42%), suggesting that car availability plays an important role in the travel arrangements of car-negotiating households. Moreover, there are clear differences between car-negotiating households and car-sufficient households in the use of PT. The use of K&R among licensed members of car-negotiating households may be motivated by household resource constraints and economic factors while the motivation for the use of K&R among licensed members of car-sufficient households must be mainly economic factors. For K&R users without a licence, intra-household interactions may be motivated by time and space constraints as well as altruism.

Intra-household interactions in PT use on weekends could be analysed in a similar way but the number of public transport tours with joint household travel at either end on weekends is too small (N = 63 tours) to provide any significant result. Although a similar pattern of interactions in PT use is found on weekends as compared to weekday pattern, the difference in median access distance of PT tours made on weekends by car-negotiating and car-sufficient households is not statistically significant (p = 0.075). Apart from a small sample size, another possible explanation is that weekend travel is mostly non-subsistence based and oriented towards shared activities with less time pressure and resource constraints due to a lower level of conflict between/amongst household members over the allocation of household resources.

5.2.6 Mode of travel and tour complexity

Apart from the travel purpose, household car ownership and the household’s spatial setting discussed above, the existing literature suggests that tour complexity is an additional factor
which influences travel mode choices. To provide a context for the current analysis, this section briefly reviews the literature on the relationship between tour complexity and mode choice. This is followed by a new method of classifying the complexity of tours which takes into account not only the number but also the spatial distribution of activities chained into a tour. The main findings are then presented that provide insights into why findings in the existing research literature conflict.  

The existing literature has reported that complex tours were less likely to be public transport based (Hensher and Reyes, 2000; Wallace et al., 2000; Cicillo and Axhausen, 2002). More recently, Ye et al., (2007) developed recursive binary probit and simultaneous logit models to examine and distinguish three possible causal relationships between tour complexity and mode choice. These were that the mode choice decision comes first and influences tour complexity; second that the number of activities chained into a tour (or tour complexity) is determined first and influences mode choice; and finally that the two choice decisions are determined simultaneously. Their research found that for both work and non-work tours, tour complexity drives mode choice rather than the choice of mode determining the incidence of chaining additional activities into a tour. Also, Krygsman et al. (2007) found that for a majority of home-based work tours, the activity decision is made before the mode decision. These findings lend credence to the hypothesis and empirical evidence that the need to make a complex tour requires the flexibility of the car mode. Other studies, however, have found evidence challenging the hypothesis that public transport is inflexible and results in less complex tours. Primerano et al. (2008) found in Adelaide that mass public transport tours on average involved more activities than car tours. Currie and Delbosc (2011) found in Melbourne that tours by train and tram were more complex than car tours (5.5% and 9.6% more stops (including ‘returning home’) respectively) while tours by bus involved 8.4% fewer stops than car driver tours. A survey in New Zealand indicated that the differences between simple and complex tours for both public transport and car were different across travel purposes with the proportional decrease in public transport use for complex tours being far greater than that in car use for work and education tours and that this reversed for non-work, non-education tours (O’Fallon and Sullivan, 2005).

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3 This section is based on the paper by this author published by Transportation Research A (Ho and Mulley, 2013b).
A common element to all but one of these studies is that tour-based analysis has so far treated tours as travel involving either single purpose or multiple purposes with little regard for whether these purposes are done at single or multiple destinations. The relationship between tour complexity and travel mode has thus been analysed with a focus on a categorical classification of tours as simple, i.e., travel involving a single purpose at single destination (SPSD) or complex, i.e., multiple purposes at multiple destinations (MPMD). The exception is the study by Currie and Delbosc (2011) where tour complexity is represented by the number of activities chained into a tour. However, approaches to examining tour complexity have not taken into account the high number of tours which are multiple purposes but single destination (MPSD).

Spatially complex tours are considered in advanced activity-based models which typically separate the tours that start and end at the workplace (i.e., work-based sub-tours) from the work tours and model them separately (Bradley and Bowman, 2006; Davidson et al., 2010). The work tour mode choice model then utilises the information from this sub-tour model to incorporate the influences that the sub-tours at work may have on the choice of travel mode for the main work tour. These approaches do consider the effect of a MPSD tour type on mode choice indirectly for work tours. However, MPSD tours are also prevalent among non-work tours and they do not necessarily use an anchor point (such as workplace) other than the home. Whether public transport tours can be as complex as car tours but for different tour complexities or whether public transport tours are always less complex is the contradiction posed in the literature. This section considers whether the activities chained into a tour are to single or multiple destinations and whether the mode used in accessing destinations is by a motorised or non-motorised mode.

An activity chained into a home-based tour was considered as sharing the destination with others, and thus a tour involves multiple purposes at a single destination if three conditions were simultaneously satisfied. First, the trip segment to that activity involved an intervening activity (i.e. not changing mode, not returning home). Second, that the intervening activity was reached by walk (other non-motorised modes were rare in the dataset) and the location was within a walkable distance of 800 meters from the immediately preceding activity. A walkable distance of 800 metres was chosen after reviewing the available literature on this topic with a special consideration on studies in Australia (O'Sullivan and Morrall, 1996; Rastogi and Krishna Rao, 2003; Burke et al., 2006; Burke and Brown, 2007; Daniels and Mulley, 2011) and the purpose of the walking trip between activities sharing a destination
which was to an activity site rather than to change mode. Third, the purpose of the immediately preceding trip segment was not ‘changing mode’. The third condition is introduced to ensure activities taking place at a single destination are all intervening activities. Using this approach, destinations and the number of activities chained into tours were equal to the total number of activities minus the number of activities sharing a destination with others (i.e., MPSD). Figure 5.8 illustrates two home-based tours with (a) being categorised as MPSD whereas (b) is not MPSD because the tour illustrated in figure (a) satisfies all three conditions specified above. The developed typology of tours classified tours without the presence of MPSD as multiple purposes at multiple destinations (MPMD) tours (Figure 5.8b) or single purpose at single destination (SPSD) tours. The latter is referred to as simple while the former is referred to as complex with the categorical classification approach. With the approach using the number of activities, SPSD tours are least complex and MPMD tours are more complex (than, e.g., SPSD).

For multiple activities at one destination, one activity is considered as the primary activity, (the main reason for visiting the destination, ordered on the same hierarchical basis) while others are referred to as secondary activities. In the example tour plotted in Figure 5.8a, work is considered as the primary activity and is also the main purpose of the whole tour. On the other hand, ‘lunch’ and ‘return to work’ are considered as secondary activities, sharing the same destination with the work activity. Primary and secondary activities do not apply to MPMD and MPSD tours whose main activity (i.e. main purpose of the entire tour) has been defined.
Using this typology of tour complexity and the home-based tour dataset, tours undertaken by public transport and car users were investigated. The dataset contained 19,860 eligible tours in which public transport and private car use were identified. The majority of tours (11,600/19,860 = 58%) are simple SPSD. Travel involving MPSD represents 9% (1,748/19,860 = 9%) of home-based tours and about one-fifth (1,748/8,260 = 21%) of ‘complex’ tours (i.e., tours with more than one intervening activities). Figure 5.9 compares modal shares by travel purpose across different level of tour complexity classified as MPSD, SPSD, and MPMD on an average day in Sydney. Although the car is the dominant mode overall, MPSD tours are much more likely than SPSD and MPMD tours to be done by public transport (33% compared to 9% and 12% respectively). Consequently, modal shares are much more equal for MPSD tours than for MPMD and SPSD tours. For instance, the average probability for car and public transport for MPSD work tours is respectively 0.490 and 0.510; in contrast to MPMD work tours of 0.873 for car and 0.127 for public transport.
Much of the literature on tour complexity focuses on the number of activities chained into a tour. To compare with other studies and using two ways of defining tour complexity, Figure 5.10 shows the difference in complexity for all modes of public transport compared to car. When activity locations are taken into account in defining tour complexity (Figure 5.10a), public transport tours are statistically significantly less complex than car tours except for the tours undertaken by ferry and on weekends. This finding supports Hensher and Reyes (2000) which concludes that as a tour becomes more complex, public transport is less likely to be used, although this study is based on a tour typology which does not necessarily take account of activity locations (for example, tours with multiple work activities are classified as simple regardless of the distance between consecutive activities). When tour complexity is measured as the number of activities within a tour (Figure 5.10b) train and bus tours on an average day and ferry tours on an average weekend day are statistically significantly more complex than car tours. This finding is consistent with results from Adelaide and Melbourne (Primerano et al., 2008; Currie and Delbosc, 2011).
(a) Average destinations and activities per tour
(b) Average activities per tour

Figure 5.10 Tour complexity by mode and day of week: two approaches to tour complexity


The breakdown of travel purposes shown in Figure 5.11 indicates differences in complexity of public transport tours relative to car tours across the two methods of defining tour complexity. When destinations visited are taken into account, public transport tours are less complex than car tours for all purposes where differences are significant. Conversely, when tour complexity is represented by the number of activities without regard to destinations, public transport tours are more complex for non-subsistence activities, especially maintenance but less complex for subsistence activities than car tours. This suggests that the choice of tour typology is instrumental in commenting and concluding on the relationship between tour complexity and mode choice. The effects on mode choice of tour complexity are analysed in this study by using the developed typology which takes into account not only the number but also the spatial distribution of activities chained into a tour.
Figure 5.11 Difference in complexity for public transport tours compared to car tours by tour main purpose: two approaches to tour complexity


Figure 5.12 shows the relationship between mode choice and tour complexity with activities chained into a tour being classified into two groups: those done at different places and those done at the same destination with others. As the number of activities done at different places chained into a tour increases, public transport use decreases. Conversely, the more activities sharing destinations with others were chained into a tour, the more likely public transport was used. Thus, combining two types of activities having different relationship patterns with mode of travel would result in an ambiguous relationship between tour complexity and mode choice as has been found in the literature, and discussed above.

Figure 5.12 Modal share of home-based tour by two indicators of tour complexity, average day in Sydney 2007 – 2010

Because public transport use increases with the number of secondary activities chained into a tour (Figure 5.12), further analysis investigated the kinds of tours in which people have tended to cluster activities into a single destination. Discretionary and maintenance activities are significantly more likely to involve MPSD than subsistence activities. The majority (80%) of weekday non-subsistence public transport tours involving MPSD were made during off-peak periods. Of weekday public transport tours involving MPSD with the main purpose being non-subsistence made during peak periods, the bus share was twice the train share. This reflects the difference in the fare system between train and bus in Sydney, where off-peak ticket fares are available for train but not for bus.

The tendency for a primary activity to have secondary activities pursued within a single destination is also investigated. Figure 5.13 shows the occurrence of secondary activities by selected primary activities (for definitions of primary and secondary activities, see Figure 5.8 above). Of tours involving MPSD, social/recreational activities appear to be chained most with personal business, shopping, and work or work-related business. Shopping and personal business also shows a high propensity to be chained with work and activities of the same types. Primerano et al. (2008) report similar results but they do not differentiate between MPMD and MPSD tours.

<table>
<thead>
<tr>
<th>Primary activity is Work/work-related (30%)</th>
<th>Primary Activity is Shopping (40%)</th>
<th>Primary Activity is Personal business (5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shopping</td>
<td>59%</td>
<td>34%</td>
</tr>
<tr>
<td>Social/Recreational</td>
<td>48%</td>
<td>61%</td>
</tr>
<tr>
<td>Work/Work-related</td>
<td>18%</td>
<td>0%</td>
</tr>
<tr>
<td>Personal Business</td>
<td>7%</td>
<td>43%</td>
</tr>
<tr>
<td>Serve Passenger</td>
<td>3%</td>
<td>9%</td>
</tr>
<tr>
<td>Education</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

% Chained with the primary activity

Note: Sum of percentages do not equal 100% because there were MPSD tours with more than one secondary activity.

Figure 5.13 Occurrence of secondary activities by selected primary activities of MPSD tours


Across the descriptive analyses presented in this section, the spatial distribution of activities appears to have an additional effect on mode choice on the top of the number of activities
chained into a tour. The effects on mode choice seem to be different across travel purposes as
does the frequency of MPSD tours. Together, these results suggest that the effect of tour
complexity on mode choice may partly be captured in models controlling for the travel
purposes. This is tested with the empirical models developed in the next chapter.

5.2.7 Travel party composition
Travel party composition as a factor in travel mode choices is investigated in this section.
Previous studies have found a strong effect in the presence of children on the travel mode of
workers and non-workers in a household (Hensher and Reyes, 2000; Vovsha et al., 2003; Ho
and Mulley, 2013b). Figure 5.14 shows the modal share across the travel party compositions
on weekdays and weekends. The travel party composition is classified into three groups
including parents and children, couples only, and others (brothers and sisters, children and
grandparents, mixed party). Each joint tour is counted by the number of participants, as
opposed to one per joint pattern.

(a) Weekday

<table>
<thead>
<tr>
<th></th>
<th>Fully joint tour by 2 persons (J1)</th>
<th>Drop-off tour (J2)</th>
<th>Pick-up tour (J3)</th>
<th>Shared rides tour (J4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walking</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b) Weekend

<table>
<thead>
<tr>
<th></th>
<th>Fully joint tour by 2 persons (J1)</th>
<th>Drop-off tour (J2)*</th>
<th>Pick-up tour (J3)*</th>
<th>Shared rides tour (J4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PT</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Walking</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Differences in modal share across travel party compositions are not significant at the 5% level.

Figure 5.14 Modal share by travel party composition, Sydney 2007 – 2010

Figure 5.14 shows a higher propensity to use car and a lower propensity to use PT for joint travel between parents and children, as compared to joint travel involving couple only or other household members. This effect appears to be stronger and more consistent across joint tour types on weekdays than on weekends. This may be due to the small weekend sample size of partially joint tours and might explain the insignificant differences between PT and car use for drop-off and pick-up patterns across travel party compositions.

5.2.8 Joint household travel by household and individual characteristics

The arrangement of joint household travel appears to be dependent on household and individual characteristics, other than household car ownership and the household’s spatial setting as presented in Section 5.2.5 above. This section considers joint household travel arrangements by household size, household lifecycle, and the individual’s age with each joint tour again being counted by the number of individual participants as opposed to one per joint tour. The former is preferred so as to bring both joint and individual tours to a common denominator for comparison. The impact of these factors on joint household travel are less obvious in the literature, as compared to other household and individual characteristics such as income, gender and employment status that are usually included in travel demand models.

Household size characterises the opportunity for household members to co-ordinate joint travel. Household lifecycle and individual’s age embody the demand for travel and restraints on mobility which give rise to joint household travel in the form of drop-off and pick-up. As with travel purpose, the effect of household size, household lifecycle and individual’s age on joint household travel arrangements is significantly different across weekdays and weekends. This section aims to explore the effect of household lifecycle stages, household sizes and individual’s ages on joint household travel, as opposed to the differences between weekdays and weekends. Thus, the following results are presented for an average weekday with a comparison between weekdays and weekends can be found in Appendix 1.

Figure 5.15 shows the distribution of joint tour types by household size with five or more persons as the upper limit. Considering five persons as the upper limit is justified as Figure 5.15 shows only a small difference in the distribution of joint tour patterns between 4-person households and 5+ person households. Single person households are not included as joint household travel is not possible. Similarly, 2-person households cannot form joint tour patterns with 3+ persons, and thus the share of these tours is zero. Figure 5.15 shows that the larger the household, the lower the share of individual tours. This may be because members of
a large household have a higher opportunity to co-ordinate joint household travel in the form of pick-up and drop-off on the way and mixed tour patterns. However, 2-person households undertake the same proportion of fully joint tour patterns (about 23%) as large households do. This is likely to be a result of a desire for companionship of households at different lifecycle stages discussed below.

Figure 5.15 Distribution of joint tour patterns by household size, average weekday in Sydney 2007 – 2010


Figure 5.16 shows variations of joint tour patterns across household lifecycle stages, which progress from single person to married couples without children, to couples with young children only, to couples with older children. Divorce and remarriage add complexity to this typical progression. Figure 5.16 shows that joint household travel arrangements are strongly linked to the presence of children and their ages. The proportion of joint tour patterns, especially partially joint tours, is not significantly different between single parent and couple parent households (p = 0.967), and thus these households are not distinguished. Joint household travel accounts for the highest share in households with the presence of young children (aged 15 years or under). The higher share of partially joint tours (J2, J3, J4) in these households may be due to the arrangement of drop-off and pick-up to meet the children’s needs. Similarly, social constraints may explain the higher share of mixed joint tour patterns (J5, J6, J7) as in Australia children under 15 years of age are not advised to stay home on their own (Tippet, 2011).
Figure 5.16 also shows partially joint travel arrangements are higher in households with older children (aged over 15 years) as compared to couple only households but the reverse is true for fully joint travel. This would be to some extent explained by the ways that households reorganise their travel patterns and responsibilities to adapt to each of these lifecycle stages. Couple households without children tend to have a high level of interdependency and companionship which is associated with a high proportion of fully joint travel. Caring for young children cuts the amount of time that a parent may otherwise spend alone or with their partner (i.e., individual travel reduces significantly) while chauffeuring children to and from school or other activities results in a high proportion of shared ride arrangements. Retaining the couple relationship in an enlarged family at this household lifecycle stage contributes to maintain fully joint travel at the same level of the couple household with no children. As children become older and more independent, both in travel and activity participation, the proportion of partially joint tours decreases as does fully joint travel.

Figure 5.16 Distribution of joint tour patterns by household lifecycle, average weekday in Sydney 2007 – 2010

*Older children (aged over 15 years) may be present in the household.*

their requirements for constant adult supervision and care. A substantial proportion of fully joint tours by preschool age children are likely to be motivated by companionship, as opposed to joint participation in a shared activity. A large proportion of mixed joint tour patterns (J5, J6, J7) undertaken by preschool age children is likely to represent a typical example of children coming along for a ride when adult household members are giving drop-off or pick-up to other household members. This is also true for children of the age groups of 6 to 10 years old and for secondary school age (11 to 15 years old), albeit to a lesser extent. Children of these age groups show a higher propensity to make travel involving shared rides (J4 and J7), reflecting their higher needs for escort to/from school and other recreational activities. People over 15 years old are more likely to make individual tours as expected.

Figure 5.17 Distribution of joint tour patterns by age group of children, average weekday in Sydney 2007 – 2010


5.3 Summary of Descriptive Results and Implications for Modelling

This chapter has presented a series of descriptive analysis of joint household travel using different units of analysis including trip, tour and daily activity-travel pattern and has compared the results with previous studies. The comparison helps draw a general picture of joint household travel across countries and highlights the importance of analysing joint household travel for a better understanding of travel behaviour. The comparison of joint household travel suggests a number of similarities internationally but it also highlights a substantial difference in the percentage of joint travel when different units of analysis are used. Joint household travel accounts for about one-fifth of total weekday travel when the unit of analysis is a trip, as compared to one-half when the unit of analysis is a tour.
The results represented in this chapter also highlight significant differences in activity participation and travel pattern between weekdays and weekends. Weekday travel is directed toward work and education activities and is distinguished by more intra-household shared ride arrangements such as drop-off and pick-up. In contrast, weekend travel is oriented toward maintenance and discretionary activities and is characterised by a high proportion of fully joint tours. The propensity to chain shared activities into joint tours is significantly higher and the median duration of these shared activities is, in general, significantly longer on weekends than on weekdays. Thus the third hypothesis about the difference between weekdays and weekends in terms of joint household travel arrangements and shared activities are strongly supported. In addition, these differences over weekdays and weekends are associated with different mode shares and hence require different models for weekend and weekday travel.

Joint household travel, either fully or partially, is prevalent in daily activity-travel patterns. These tours account for more than half of the total home-based tours on weekdays and about 61% on weekends. The differences in modal share are significant across joint tour types, controlling for the effect of household car ownership, travel party composition, weekdays and weekends. These findings support the first hypothesis that household interactions in term of joint travel underlie observed individual mode choice and suggest the relevance of modelling joint household travel as a part of the mode choice decision.

Descriptive analyses presented in this chapter have partially addressed the hypotheses about the motivation and constraints on joint household travel and individual mode choice (hypotheses 1) and the differences between weekdays and weekends in terms of joint household travel (hypothesis 3). Joint household travel arrangements appear to be motivated by household resources and the household’s spatial setting with joint travel and mode choice behaviour being found to be different significantly between car-negotiating and car-sufficient households. The investigation into the access mode, access distance and driving licence status of PT users from households with different levels of car ownership suggests that car availability and spatial separation play an important role in joint travel arrangements and mode choices. Companionship as a motivation for joint household travel finds less support although an interesting result emerges that the differences in walking access distance between PT tours with and without joint travel at either end are not significant. Evidence is also found to support the role of social and mobility constraints in joint household travel with younger children being more likely to participate in mixed joint tour patterns and less likely to travel
independently. Situational factors such as travel purpose and travel party composition are highly correlated with joint household travel. Such motivation and constraints need to be incorporated in modelling with corresponding variables. Also, the comparison of modal shares by tour complexity suggests that it is likely to be relevant predictor of travel mode choices. Chapter 6 discusses in detail the selection of explanatory variables for travel mode choices incorporating joint household travel arrangements.
CHAPTER 6. EMPIRICAL MODELS

Chapter 1 and Chapter 2 identify the research questions and the research hypotheses of this study. To test these research hypotheses, the Sydney Greater Metropolitan Area is chosen as the case study whose available data sources have been described in Chapter 3. Chapter 4 has described in details the steps taken to transform the Sydney HTS data into the datasets used for this study with Chapter 5 providing a series of descriptive analyses which have partially addressed hypotheses 1 and 3 identified in Section 2.6. However, the tests which are possible with descriptive analyses suffer from the limitation of being unable to confirm the strength of the relationship. For example, the correlation between joint household travel and travel mode may have a shared underlying causal link such as travel time, travel cost, or spatial and temporal synchronisation of household members’ activities. Similarly, the observed differences between weekday and weekend travel, in terms of joint household travel, may be created by the distribution of activities over weekdays and weekends.

To fully consider the hypotheses identified in Section 2.6, this chapter develops empirical models which control for household and individual characteristics, the household’s spatial setting, and tour attributes. In this chapter, the typology of joint household tours described in Chapter 4 is used to develop discrete choice models which incorporate intra-household interactions into individual mode choice decisions.

The chapter starts with a specification of the dependent variable, the decision-making unit, and the simplifying assumptions employed in the empirical models. This is followed by a discussion on the choice set availability and a specification of explanatory variables. The estimation results are then presented, both for weekday and weekend models. Differences between weekday and weekend travel are quantified with policy analysis. The penultimate section discusses the advantages of a joint household travel analysis over an individual travel analysis. This chapter ends with a summary of the estimation results.

6.1 Specification of the Dependent Variable and Model Assumptions

The construction of the dependent variable for modelling proceeds from the identification of joint household tour patterns and tour main travel modes described in Chapter 4. The frequently observed joint tour patterns are summarised in Figure 4.16 (p. 104) and the identification of the tour’s main travel mode is discussed in Section 4.3. Ideally, a group-based model such as the generalised parallel choice constrained logit developed in Chapter 3
should be used to capture joint household decisions in multiple-person households and allow different household members to play different roles. An application of this modelling approach to the empirical data raises issues of estimation and application as the approach requires the same choice of joint household outcome for all persons involved in a joint tour pattern yet the empirical data show many possible combinations of joint tour patterns in a multiple-person household and some joint tour patterns spread over two home-based tours. The shared ride pattern (J4) is a typical example with the chauffeur returning home in between rides, forming two separate tours whilst the passenger makes only one tour. To meet the same joint choice outcome requirement of the group-based modelling approach, all tours undertaken by each household member needs to be concatenated and assembled into a daily travel pattern. Coding individual tours into a daily activity-travel pattern creates about 800 unique alternatives for weekday travel and about 450 unique alternatives for weekend travel. With the most frequent daily activity-travel patterns shown in Appendix 2, the choice structure is still very complex with many individual choices belonging to multiple joint household outcomes. The specification of multiple allocation parameters to deal with this issue resulted in a model which was so complex that the estimation would not converge. As a result, an individual-based modelling approach is used.

Using the individual-based approach, the individual choices of joint travel patterns and travel modes are modelled simultaneously at the tour level by a nested logit model shown in Figure 6.1. 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 regarded as having matched their activity agendas so as 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 Figure 6.1 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.

Figure 6.1 Tree structure for mode choice model with joint household travel

The lower level represents individual’s choice of main travel mode between public transport, 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 embody the household members’ agreement upon time and space constraints for the journey.

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. The specification of explanatory variables is described in Section 6.3 after the availability of alternatives in individual choice sets is discussed in the next section.
6.2 Choice Set Availability Restrictions

The choice structure considers all possible combinations of joint tour patterns and travel modes. However, the availability of joint tour patterns and travel modes in the choice sets of individuals need to be restricted to reflect the reality as follows:

- Travel patterns involving joint household travel are not available to single person households as joint household travel is not possible. In other words, single person households only have at most three alternatives corresponding to the individual tour pattern (J9) in their choice set.

- Joint tour patterns which involve more than two persons including fully joint tours (J1) with three or more household members, and mixed tour patterns (J5, J6, J7) are not available to 2-person households. As illustrated in Figure 4.16 (p. 104), these joint tour patterns require at least 3 persons to form. Thus, individuals from 2-person households have at most 15 alternatives corresponding to 5 joint tour patterns of individual (J9) and partially joint tours (J2, J3, J4, and J8) in their choice set.

- Households with 3 persons have all identified joint tour patterns in their choice set except for the fully joint tour pattern by 4 persons which is only available to households with 4 or more persons.

- Walking as the main mode of travel is not available for tours with any trip segments being longer than 5 km except for when it was chosen. This is supported by previous studies (e.g., Ewing et al., 2004) and the observed data with 99% of walking tours having all trip segments shorter than 5 km.

6.3 Specification of Explanatory Variables

The specification of explanatory variables for the empirical model is based on theoretical relevance and statistical tests. Potential explanatory variables found in the datasets are first related to joint household tour patterns and tour’s main modes using a series of descriptive analysis, some of which have been presented in Chapter 5. Variables that would best explain the underlying intra-household interaction structure and that are of the type that would be available for forecasting purposes are then tested with the empirical model. Potential explanatory variables are classified into five categories based on their theoretical relevance and discussed through subsections that follow:

- Household structure and household resources
- Travel choice context
- Social and mobility constraints
- Spatial setting
• Tour attributes

6.3.1 Household structure and household resources

Household lifecycle, as discussed in Section 5.2, is central to the understanding of intra-household interactions in travel behaviour in general and travel mode choice in particular. New dummy variables are created from the original household type variable to explain different patterns of intra-household joint travel. These dummy variables indicate whether the household type is couples only, family with young children aged 15 years old or under, family with children aged over 15 years only with other household types being treated as the reference value.

Household resources, which can be described by household socio-demographic characteristic variables such as household income, household size, and the number of cars vs. the number of driving licence holders, are important indicators of daily activity and mobility of a household. While household lifecycle provides general information on the type of a household, household resources explicitly point to household-specific circumstances such as the mobility investment and household income relevant for the travel pattern of that household. Households are classified into three groups according to their annual income: low-income households (under $31,200), middle-income households ($31,200 to $67,600) and high-income households (over $67,600). The size of a household is a raw count number of people living in the same household, but this variable is highly correlated with household type. Thus, only one dummy variable is specified for a household with 5 or more persons. This is to capture the higher opportunities for large households to co-ordinate joint household travel in the form of pick-up, drop-off, and mixed tours.

Household resources are further characterised by the level of car availability for household use, described with three dummy variables indicating no car households, car-negotiating households or car-sufficient households. Car-negotiating households, as defined before, are households with fewer cars than the number of licence holders. Car-sufficient households are households with at least as many cars as licence holders. Using the Sydney HTS data, a vehicle is defined as a household car if three conditions are simultaneously satisfied. First, its body type must be car, 4WD, van or utility vehicle; second, the vehicle is owned by a household member; and third, the vehicle is registered for private use. Thus, company owned cars, cars registered for business use only and vehicles type motorcycle and truck are not counted as household cars. Similarly for licence holders where a licence holder is defined as a
household member holding a valid car driving licence which allows them to drive a car on their own. That is, a person who holds a car learning licence is not considered as a licence holder.

6.3.2 Travel choice context

Situational factors explain the choice situation that each household member and the household as a whole faces in choosing their activity-travel patterns. Situational factors, which are represented by travel purpose, travel party composition, type of working hours and time schedule synchronisation are critical to the understanding of intra-household interactions in travel mode choices. Four dummy variables are created to represent the main travel purpose of a tour including work, education, maintenance activities (shopping, drop-off and pick-up, personal business), and discretionary activities (social, recreation). The travel party composition is represented by two dummy variables indicating the composition of couples only or parents and children with other party compositions being treated as the reference case.

Type of working hours is indicative of flexibility at work and is represented by two dummy variables. The ‘fully flexible working hours’ and ‘partially flexible working hours’ variables indicate whether the worker has a full or partial flexibility at work with ‘fixed working hours’ being the reference base. These two dummy variables are included to explain travel pattern differences between workers with and workers without flexible working hours. The differences may result from situational factors such as the nature of the choice task and the perceived risks of, for example, being late if a stop to drop-off children at school is chained into a commuting tour of the worker without flexible working hours.

Assistance with the cost of commuting from employers explains a motivation for workers to use a specific travel mode, depending on the way in which the assistance is given. There is more incentive for commuters to use public transport if public transport fares are paid by the employer. Similarly, commuters are more likely to drive if the company provides free parking or pays parking costs. Dummy variables are created and tested in the empirical model for the different types of employer assistance including free parking/parking costs provided, company car/car pooling provided, car costs/fuel cost paid, and public transport fares paid with no assistance being treated as the reference case.

Time schedule synchronisation is indicative of the opportunity for joint household travel in the form of drop-off and pick-up. A dummy variable is created to indicate the synchronisation
of work and school schedule times. This variable is applied to commuting tours of the workers in households that have at least one student going to school on the same day. Workers with a synchronised time with the children’s school time are expected to combine commuting with chauffeuring children to/from school.

6.3.3 Social and mobility constraints

People with mobility constraints usually encounter more barriers in planning and implementing their activities. Young children, for instance, are usually reliant on their parents and other adult household members to travel and participate in various activities such as education, recreation and sport. Young children also need constant adult supervision and care when they participate in in-home or out-of-home activities. This social constraint suggests young children should neither stay at home alone nor travel independently, and thus they may ‘come along for a ride’ when adult household members perform their activities. The extent to which social and mobility constraints impact upon children’s activities and travel depends on their ages, as shown previously in Figure 5.17. Thus, for the empirical work, children in the household are split into 4 age groups and represented by 4 dummy variables: children aged up to 5 years, children aged 6 to 10 years, children aged 11 to 15 years, and children over 15 years old. This is to reflect the different needs and constraints that children at different ages place on household activity-travel decisions. The first variable describes preschool age children who require constant adult supervision and care; the second and third variables describe school age and pre-driving age children who need less supervision but perhaps more escorting to school and other social, recreational activities. Children aged 16 or over are of legal driving age, and are therefore assumed to be more independent in their activity participation and travel. This age group is treated as the reference in the model.

Social and mobility constraints on children’s travel also mean support is provided to assist children in activity participation. Traditionally, providing support and giving care is linked to the role of a mother while a father acts as an income provider. Gender-based roles may be more pronounced in households with children of different age groups. Of particular interest are preschool age children (0 to 5 years old) who need constant supervision, usually from the mother, and pre-driving age (6 to 15 years old) children who require escorts to/from school and other activities. Two interaction variables are created to distinguish the roles of mothers and fathers in households with mixed aged children.
Other individual characteristics that embody mobility restrictions which are tested in the empirical models include driving licence status and labour force status. The total household drivers are used previously in conjunction with household cars to define household car availability but licence status is also relevant to personal mobility. Driving licence is therefore used as a variable at both household and individual levels. Labour force status explains a motivation for tour making to some specific activities but a constraint for participating in other activities. For example, full-time workers are more likely to make working tours but less likely to participate in maintenance activities on weekdays; their commuting patterns therefore tend to be simple with long working hours in between. Consequently, the demand for a household car by the full-time worker may be lower than that of their partner who runs household errands. This effect is expected to be pronounced in car-negotiating households, and thus two interaction variables are created for workers and non-workers in car-negotiating households. Other dummy variables representing people over 15 years old and not in the labour force include student (high school or college) and retired. Students may have a limited access to a household car while a physical restriction may prevent retirees from driving. Both students and retirees may be eligible for discounted public transport fares. These factors work in favour of public transport use.

6.3.4 Spatial setting
The household’s spatial setting is indicative of space and time constraints faced by all household members in travelling to work, education and in participating in maintenance and leisure activities (either solo or shared). The spatial setting of a household is represented by the built environment at the place of residence, the place of work and education, and the separation between these locations. Home, workplace and school locations are long term decisions and they are treated as exogenous in this model. The land use data tested in the empirical model include access to public transport from home, workplace and school. The spatial separation between home, school and workplace is also tested in the model in addition to public transport density, land use mix and aspects of road network design and layout. These variables are specified next.

Access to public transport service from home is measured by the walking distance from home to the closest high frequency bus stop, defined as having 12 or more services per hour during the am-peak (7–9 am on a working day). As most train stations and ferry wharfs in Sydney are well served by feeder buses, this variable is also a good proxy for access to train and ferry where these services are available. Access to public transport service at the place of work and...
School is measured by the walking distance from these locations to the nearest public transport node. All of these distance variables are measured using the real X and Y coordinates of the home, school and workplace for each observation in the dataset.

The spatial separation between home and workplace is represented by the road network distance between them. A similar measure is used for the spatial separation between home and school. To capture the effect of a route deviation on escorting students to/from school en route to work, a detour distance is used. The detour distance to work due to escorting students to/from school is equal to the difference in distance between the shortest route from home to work via children’s school and the shortest route between home and work without stopping at the school. All distance variables based on the place of work and school are respectively applied to persons with their occupation being worker and student, either full-time or part-time. For persons who are not a student or a worker, these variables have zero values.

In addition to access distance to public transport described above, public transport kernel density is used to capture aspects of public transport network design and layout. Tracy et al. (2011) provided a detailed process for estimating public transport kernel density for a specified spatial area as follows. First, each public transport node is considered as a generating point with a kernel function and a kernel radius. The kernel function has the highest value (strongest effect) at the source point and decreases smoothly to zero (no effect) at the distance equal to the kernel radius. Next, this density surface is overlaid with a raster grid of cells and the kernel value for each cell is the summation of all overlapping kernel function values. If the kernel density is required for the travel zone geography, the average kernel density for each travel zone is then the mean kernel value of all cells in that travel zone. Cells that fall on the boundaries of travel zones are proportionally split among these zones. The advantage of using the kernel density over a point density measure is that the influence of train stations is considered for all nearby travel zones rather than only one travel zone that contains the train station (Tracy et al., 2011). This study has built on this idea and has used service frequency in the extended am-peak (6 am – 10 am) to weight the kernel values thus reflecting additional utility derived from a good service frequency on the top of the availability of the train service. In creating the rail kernel density measure, there is a need to select the bandwidth (search radius) and cell size. Whilst the bandwidth is more important in determining kernel density performance, the choice for both is context dependent (Fotheringham et al., 2000; Anderson, 2009). In this research a bandwidth of 2 km was chosen, based on the distance distribution of access trips to train stations (Xu et al., 2011).
The literature identifies cell size as being empirically determined (Anderson, 2009). In this study, a cell size of 100 m was used as the best trade-off between achieving density values in all travel zones and calculation time. Figure 6.2 shows the weighted rail kernel density estimated using these parameters and TransCAD for the central area of Sydney SD.

Figure 6.2 Rail kernel density weighted by service frequency, central area of Sydney SD
Data sources: Developed from GIS layers.

While access to public transport service and commuting distance (for education and work purposes) is previously found to influence mode choice for subsistence activities and discussed above, mixed land use is commonly cited as a factor influencing mode choice for
non-subsistence activities (Bradley and Bowman, 2006; Chatman, 2008; Ewing and Cervero, 2010). Mixed land use and an opportunity density is computed using the travel zone layer showing zone boundaries and centroids with zone attributes including population and total employment by industry. 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:

\[
\text{Mixed opportunities per unit area} = \frac{\sum \text{Opportunity}_{it} \cdot \frac{\sum p_{it} \ln(p_{it})}{\ln(n)}}{\text{Area}_i}
\]  

(6.1)

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 (Cervero and Kockelman, 1997). The advantage of the 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 layers. 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). Figure 6.3 shows the road network layout in two contrasting areas with the pattern on the right being more connected and easier for walking. It also shows travel zones vary widely in terms of geography and local road network. To resolve issues of the effect of geographical aggregation on the correlation between land uses and mode choice, an 800 m buffer around the travel zone centroid is compared against the travel zone boundary for these measures to choose the better aggregation. It would be better to use a buffer around the individual’s home but the real X and Y coordinates of the home are not available to this study due to confidentiality issues.
As with access to public transport service, the land use mix and design aspects of road network are measured at both origin and destination of the tour. As mode choice decisions are not likely to be a function of land use patterns at intermediate stops between the home and the main destination, the land use patterns at these intermediate stops are not considered in this study (Frank et al., 2008). However, the presence and the spatial distribution of intermediate stops on a tour are likely to influence the choice of main travel mode (see Section 5.2.6). Thus, home and destination places that are characterised by a mix of opportunities and connected streets may release the need for a car to access these intermediate stops, and this in turn influences the choice of main travel mode.

### 6.3.5 Tour attributes

The level of services including travel times and travel cost are important to mode choice decisions. Four variables including travel cost, in-vehicle travel time, walk time and wait time are used to characterise the level of services of different modes. For public transport mode, the travel cost is the public transport fare for that journey, imputed from the skim matrix with adjustments to fares for concession holders and long term passes. For car mode, the travel cost is the behavioural cost of fuel consumption and tolling fee (if applicable), adjusted for vehicle occupancy and vehicle fuel consumption. These level-of-service variables were calculated for each tour as a sum over all trip segments chained into a tour. As is common in the literature (e.g., Frank et al., 2008; Nurul Habib et al., 2011), other costs associated with owning a car (long term decision) are not considered in the mode choice model (short term decision).
Tour complexity is represented by two effects coded variables. The variable MPMD represents the tour type with multiple purposes at multiple destinations and the variable MPSD represents the tour type with multiple purposes at single destination. Effects coding was used to compare average modal shares for each type of tour complexity with the grand mean (average across all levels of tour complexity) rather than the use of dummy coding where the comparison would be with a base group (SPSD). Comparisons with the base group (i.e. SPSD) are possible but not desired because average modal shares for simple tours are not usually available. Effects coding is alternative to dummy coding in which an attribute with \( L \) levels is transformed into \( L - 1 \) variables with the reference level being coded as \(-1\) instead of \(0\) (Bech and Gyrd-Hansen, 2005; Molin and Timmermans, 2010). Each effects coded variable is set equal to \(1\) when the attribute is present, equal to \(-1\) if the reference case is present, and equal to \(0\) otherwise (see an illustration in Table 6.1).

Table 6.1 Illustration of effects coding vs. dummy coding for tour complexity

<table>
<thead>
<tr>
<th>Tour complexity</th>
<th>Effects coded variables</th>
<th>Dummy coded variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPMD</td>
<td>MPSD</td>
</tr>
<tr>
<td>MPMD</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>MPSD</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>SPSD</td>
<td>-1</td>
<td>-1</td>
</tr>
</tbody>
</table>

*Note: the reference is SPSD.*

Table 6.2 and Table 6.3 provide an overview of the explanatory variables discussed above. Their descriptive statistics are provided for both weekdays and weekends based on tours to which the variables are applied. The distribution of households and individuals in the weekday and weekend samples are quite similar, reflecting the random sampling method of the Sydney HTS. This suggests that any difference in travel behaviour between weekdays and weekends is not likely to be a result of the sample. Weekday and weekend differences in the distribution of wait time, rail density, mixed opportunities and travel purposes at the main destination are noticeable. On average, wait time is much longer on weekends than on weekdays \((p < 0.001)\), reflecting a lower level of weekend public transport service in Sydney. On average, the main destination of a weekend tour has a significant lower \((p < 0.001)\) rail density and opportunity density than the destination of a weekday tour does. This suggests weekend travel is more oriented towards outer areas, probably for recreation.
Table 6.2 Descriptive statistics of household, individual and choice situation variables

<table>
<thead>
<tr>
<th>Variable description</th>
<th>Weekday Mean</th>
<th>Weekday Std. Dev</th>
<th>Weekend Mean</th>
<th>Weekend Std. Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Household structure and household resources</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Couple household with no children (1/0)</td>
<td>.18</td>
<td>.38</td>
<td>.20</td>
<td>.40</td>
</tr>
<tr>
<td>Household with young children (1/0)</td>
<td>.45</td>
<td>.50</td>
<td>.40</td>
<td>.49</td>
</tr>
<tr>
<td>Household with older children only (1/0)</td>
<td>.17</td>
<td>.38</td>
<td>.18</td>
<td>.39</td>
</tr>
<tr>
<td>Annual household income A$ ~ 31.2k–67.6k (1/0)</td>
<td>.22</td>
<td>.41</td>
<td>.21</td>
<td>.41</td>
</tr>
<tr>
<td>Annual household income &gt;A$ 67.6k (1/0)</td>
<td>.64</td>
<td>.48</td>
<td>.65</td>
<td>.48</td>
</tr>
<tr>
<td>Household with 5 or more persons (1/0)</td>
<td>.23</td>
<td>.42</td>
<td>.21</td>
<td>.41</td>
</tr>
<tr>
<td>No-car household (1/0)</td>
<td>.09</td>
<td>.28</td>
<td>.09</td>
<td>.29</td>
</tr>
<tr>
<td>Car-negotiating household (1/0)</td>
<td>.32</td>
<td>.47</td>
<td>.33</td>
<td>.47</td>
</tr>
<tr>
<td><strong>Travel choice context</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work tour (1/0)</td>
<td>.28</td>
<td>.45</td>
<td>.07</td>
<td>.26</td>
</tr>
<tr>
<td>Education tour (1/0)</td>
<td>.12</td>
<td>.33</td>
<td>.00</td>
<td>.06</td>
</tr>
<tr>
<td>Maintenance (1/0)</td>
<td>.38</td>
<td>.49</td>
<td>.47</td>
<td>.50</td>
</tr>
<tr>
<td>Discretionary (1/0)</td>
<td>.21</td>
<td>.41</td>
<td>.46</td>
<td>.50</td>
</tr>
<tr>
<td>Tour involved couples only (1/0)</td>
<td>.10</td>
<td>.29</td>
<td>.16</td>
<td>.37</td>
</tr>
<tr>
<td>Tour involved parents and children (1/0)</td>
<td>.36</td>
<td>.48</td>
<td>.37</td>
<td>.48</td>
</tr>
<tr>
<td>Worker with fully flexible working time (1/0)^a</td>
<td>.02</td>
<td>.14</td>
<td>.02</td>
<td>.15</td>
</tr>
<tr>
<td>Worker with partly flexible working time (1/0)^a</td>
<td>.18</td>
<td>.39</td>
<td>.17</td>
<td>.38</td>
</tr>
<tr>
<td>Free parking provided (1/0)^a</td>
<td>.35</td>
<td>.48</td>
<td>.34</td>
<td>.47</td>
</tr>
<tr>
<td>Parking costs provided (1/0)^a</td>
<td>.07</td>
<td>.25</td>
<td>.06</td>
<td>.24</td>
</tr>
<tr>
<td>Company car provided (1/0)^a</td>
<td>.13</td>
<td>.34</td>
<td>.13</td>
<td>.34</td>
</tr>
<tr>
<td>Car costs provided (1/0)^a</td>
<td>.17</td>
<td>.38</td>
<td>.16</td>
<td>.36</td>
</tr>
<tr>
<td>Fuel costs provided (1/0)^a</td>
<td>.19</td>
<td>.39</td>
<td>.18</td>
<td>.38</td>
</tr>
<tr>
<td>Car sharing/pooling provided (1/0)^a</td>
<td>.01</td>
<td>.09</td>
<td>.01</td>
<td>.09</td>
</tr>
<tr>
<td>Public transport fares provided (1/0)^a</td>
<td>.02</td>
<td>.15</td>
<td>.03</td>
<td>.16</td>
</tr>
<tr>
<td>Synchronisation of work and school times (1/0)^b</td>
<td>.20</td>
<td>.40</td>
<td>.00</td>
<td>.00</td>
</tr>
<tr>
<td><strong>Social and mobility constraints</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children aged up to 5 (1/0)</td>
<td>.08</td>
<td>.27</td>
<td>.07</td>
<td>.25</td>
</tr>
<tr>
<td>Children aged 6 to 10 (1/0)</td>
<td>.06</td>
<td>.24</td>
<td>.06</td>
<td>.23</td>
</tr>
<tr>
<td>Children aged 11 to 15 (1/0)</td>
<td>.06</td>
<td>.24</td>
<td>.06</td>
<td>.23</td>
</tr>
<tr>
<td>Student over 15 years old (1/0)</td>
<td>.11</td>
<td>.31</td>
<td>.12</td>
<td>.33</td>
</tr>
<tr>
<td>Retiree (1/0)</td>
<td>.09</td>
<td>.28</td>
<td>.09</td>
<td>.28</td>
</tr>
<tr>
<td>Mother of mix aged children (1/0)</td>
<td>.03</td>
<td>.18</td>
<td>.02</td>
<td>.14</td>
</tr>
<tr>
<td>Father of mix aged children (1/0)</td>
<td>.02</td>
<td>.14</td>
<td>.02</td>
<td>.12</td>
</tr>
<tr>
<td>Car licence holder (1/0)</td>
<td>.69</td>
<td>.46</td>
<td>.71</td>
<td>.46</td>
</tr>
</tbody>
</table>

*a Applied to worker's tours only; ^b Applied to work tours only; ^c Applied to education tours only.
Table 6.3 Descriptive statistics of land use and tour attribute variables

<table>
<thead>
<tr>
<th>Variable description</th>
<th>Weekday Mean</th>
<th>Weekday Std. Dev</th>
<th>Weekend Mean</th>
<th>Weekend Std. Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spatial setting (land use)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance from home to closest high freq. bus stop (km)</td>
<td>1.26</td>
<td>3.30</td>
<td>1.23</td>
<td>2.93</td>
</tr>
<tr>
<td>Distance from work to PT (km)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>.33</td>
<td>1.00</td>
<td>.29</td>
<td>.52</td>
</tr>
<tr>
<td>Distance from school to PT (km)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>.22</td>
<td>.74</td>
<td>.24</td>
<td>.19</td>
</tr>
<tr>
<td>Detour to work (km)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.59</td>
<td>8.16</td>
<td>.00</td>
<td>.00</td>
</tr>
<tr>
<td>Distance from home to work (km)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>15.74</td>
<td>16.74</td>
<td>13.59</td>
<td>15.49</td>
</tr>
<tr>
<td>Distance from home to school (km)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>6.93</td>
<td>9.74</td>
<td>14.95</td>
<td>19.43</td>
</tr>
<tr>
<td>Rail weighted kernel density, Origin</td>
<td>.08</td>
<td>.22</td>
<td>.09</td>
<td>.24</td>
</tr>
<tr>
<td>Rail weighted kernel density, Destination</td>
<td>.21</td>
<td>.48</td>
<td>.17</td>
<td>.39</td>
</tr>
<tr>
<td>Mixed opportunities per unit area (’000s/km²), Origin</td>
<td>.49</td>
<td>2.25</td>
<td>.57</td>
<td>2.24</td>
</tr>
<tr>
<td>Mixed opportunities per unit area (’000s/km²), Destination</td>
<td>3.21</td>
<td>9.92</td>
<td>2.38</td>
<td>7.73</td>
</tr>
<tr>
<td>Road link density (’000s/km²), Origin</td>
<td>.10</td>
<td>.09</td>
<td>.11</td>
<td>.09</td>
</tr>
<tr>
<td>Road link density (’000s/km²), Destination</td>
<td>.13</td>
<td>.11</td>
<td>.12</td>
<td>.10</td>
</tr>
<tr>
<td>Pseudo node density (’000s/km²), Origin</td>
<td>1.70</td>
<td>1.92</td>
<td>1.60</td>
<td>1.75</td>
</tr>
<tr>
<td>Pseudo node density (’000s/km²), Destination</td>
<td>1.46</td>
<td>1.43</td>
<td>1.58</td>
<td>2.15</td>
</tr>
<tr>
<td><strong>Tour attributes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel cost (A$ 2008)</td>
<td>3.44</td>
<td>4.95</td>
<td>3.05</td>
<td>4.31</td>
</tr>
<tr>
<td>In-vehicle time (minute)</td>
<td>44.21</td>
<td>46.13</td>
<td>43.08</td>
<td>45.00</td>
</tr>
<tr>
<td>Walk time (minute)</td>
<td>28.46</td>
<td>21.25</td>
<td>26.96</td>
<td>22.50</td>
</tr>
<tr>
<td>Wait time (minute)</td>
<td>13.24</td>
<td>26.31</td>
<td>22.29</td>
<td>42.51</td>
</tr>
<tr>
<td>SPSD (1/0/-1)</td>
<td>.22</td>
<td>.98</td>
<td>.30</td>
<td>.96</td>
</tr>
<tr>
<td>MPSD (1/0/-1)</td>
<td>-.51</td>
<td>.67</td>
<td>-.57</td>
<td>.63</td>
</tr>
<tr>
<td>MPMD (1/0/-1)</td>
<td>-.32</td>
<td>.89</td>
<td>-.37</td>
<td>.89</td>
</tr>
</tbody>
</table>

<sup>b</sup> Applied to work tours only; <sup>c</sup> Applied to education tours only.

Not all variables listed in Table 6.2 and Table 6.3 could be included in the model at the same time because of correlations between variables. For example, of the different transport-related fringe benefits provided to the worker by their employers, the provision of a company car, car costs and fuel costs are highly correlated with their pair-wise correlation coefficients being higher than 0.80. When correlations occur, the more theoretically relevant variables are chosen to include in the final model specification. When the choice of correlated variables cannot be decided on their theoretical relevance, such as the three transport-related fringe benefits mentioned above, they are judged on the statistical ground. That is, a variable that produces the highest model fit is selected for the final model specification. Conversely, for variables which have a theoretical underpinning and no correlation issue but their estimation coefficients are not significant, their interactions with other variables are created and tested in the empirical model. If none of the created interaction variables is significant, then the
variables are removed from the model except where otherwise indicated. This is discussed further in the model estimation results and their interpretation in the following sections.

6.4 Model Estimation Results

Sections 6.1 to 6.2 have discussed the model structure, the decision-making unit, the simplifying assumptions, and the way to embed joint household travel arrangements into an individual model of travel mode choice. Section 6.3 has identified potential explanatory variables of individual choice of joint tour patterns and tour’s main travel mode. Using the empirical data constructed from the Sydney HTS (described in Chapter 4) and NLOGIT 5.0, two nested logit models, one for weekday and one for weekend, are estimated. This section presents and compares the estimation results of these two models.4

6.4.1 Model fit statistics and inclusive value parameters

Table 6.4 shows the model fit statistics and inclusive value parameters for both weekend and weekday models. These final models were built up by introducing one set of explanatory variables at a time, starting with the most theoretically relevant variables to check for an improvement in model fit and any correlation issue (discussed above). The weekday model includes 30 alternatives that correspond to 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. Considering three household members as a maximum number in weekday modelling is justified by reference to the empirical data with Figure 5.4 (p. 113) showing only small number of joint household tour patterns with four or more participants on weekdays. The weekend model has 24 alternatives grouping into 8 nests, based on joint tour patterns.

4 A journal paper based on the weekday analysis has been published in Ho and Mulley (2013a). This paper was previously presented to the 35th Australasian Transport Research Forum and won the John H. Taplin Prize awarded to the best research paper. The weekend analysis and its comparison with weekday travel patterns has been published in Transportation journal (Ho and Mulley, 2013c). This paper was previously presented to the 92nd Annual Meeting of the Transportation Research Boards.
Table 6.4 Summary statistics of weekday and weekend tour-based mode choice models

<table>
<thead>
<tr>
<th>Summary statistics</th>
<th>Weekday</th>
<th>Weekend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of observations</td>
<td>16,522</td>
<td>6,495</td>
</tr>
<tr>
<td>Number of alternatives</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td>Number of parameters</td>
<td>107</td>
<td>91</td>
</tr>
<tr>
<td>Log likelihood at convergence</td>
<td>-29,781</td>
<td>-10,432</td>
</tr>
<tr>
<td>Log likelihood at market shares</td>
<td>-35,896</td>
<td>-12,015</td>
</tr>
<tr>
<td>Log likelihood at zeros</td>
<td>-56,195</td>
<td>-20,641</td>
</tr>
<tr>
<td>Mc-Fadden adjusted R-squared (vs. zeros)</td>
<td>0.468</td>
<td>0.495</td>
</tr>
<tr>
<td>Mc-Fadden adjusted R-squared (vs. constants)</td>
<td>0.167</td>
<td>0.124</td>
</tr>
</tbody>
</table>

**Inclusive value parameters*|

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Weekday</th>
<th>Weekend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual tour (J9)</td>
<td>0.656 (10.0)</td>
<td>1.0 (fixed)</td>
</tr>
<tr>
<td>Joint in middle tour (J8)</td>
<td>0.420 (5.50)</td>
<td>1.0 (fixed)</td>
</tr>
<tr>
<td>Fully joint tour by 2 persons (J1)</td>
<td>0.653 (5.78)</td>
<td>0.723 (4.04)</td>
</tr>
<tr>
<td>Fully joint tour by 3 persons (J1)</td>
<td>0.488 (8.64)</td>
<td>0.459 (6.85)</td>
</tr>
<tr>
<td>Fully joint tour by 4+ persons (J1)</td>
<td>n/a</td>
<td>0.477 (4.49)</td>
</tr>
<tr>
<td>Drop-off tour (J2)</td>
<td>0.468 (13.6)</td>
<td>0.731 (3.00)</td>
</tr>
<tr>
<td>Pick-up tour (J3)</td>
<td>0.450 (13.5)</td>
<td>0.430 (6.00)</td>
</tr>
<tr>
<td>Shared rides tour (J4)</td>
<td>0.339 (26.0)</td>
<td>0.325 (7.91)</td>
</tr>
<tr>
<td>Joint and drop-off tour (J5)</td>
<td>0.407 (9.62)</td>
<td>0.278 (7.48)</td>
</tr>
<tr>
<td>Joint and pick-up tour (J6)</td>
<td>1.0 (fixed)</td>
<td>0.278 (7.48)</td>
</tr>
<tr>
<td>Joint and shared rides tour (J7)</td>
<td>0.457 (4.64)</td>
<td>0.278 (7.48)</td>
</tr>
</tbody>
</table>

* t-values vs. 1.0 are in parentheses; n/a = not applicable in the weekday model; Shaded cells in the weekend column indicate joint tour patterns combined for modelling.

As shown in Table 6.4 above, joint tour patterns are 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. 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. Again, empirical data have driven this decision with fully joint tour by 4+ persons accounting for a substantial proportion on weekends but only a minor proportion on weekdays. Splitting fully joint tours by the travel party size is important for policy implications such as those relating to high occupancy toll (HOT) lanes and this is possible with the sample size in the dataset.
As indicated by the Mc-Fadden adjusted R-squares, both models fit reasonably well to the data and the set of explanatory variables helps explain a substantial proportion of variation in the data. Setting one inclusive value (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. In other words, the empirical data support this modelling structure. 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, public transport 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 the activity-based travel behaviour point of view, where travel is considered as a derived demand, these results are consistent with expectations.

6.4.2 Estimation results for the upper model: joint travel arrangement

Table 6.5 shows the parameter estimates for variables affecting the propensity for household members to arrange joint activities and travel into home-based tours on weekdays and weekends. Table 6.5 shows all estimated parameters have the expected sign and plausible magnitudes, as discussed further below. Considering the separate joint tour patterns on weekdays, it can be seen that the incidence of particular joint tour patterns are strongly associated with person type. Preschool children, up to 5 years old, have a significantly greater propensity to accompany adult household members whilst these adults perform drop-offs/pick-ups to other household members (indicated by positive estimates for mixed joint tour patterns J5, J6, J7). When travelling to participate in an activity, preschool children are both dropped off and picked up (J4), if they are not fully accompanied. Similarly, elementary school students (aged 6 – 10) and secondary school students (aged 11 – 15) are more likely to receive rides but they also join with adult household members giving rides to another household member.
Table 6.5 Estimation results for individual choice of joint tour patterns, Sydney 2007 – 2010

(b) Weekday

<table>
<thead>
<tr>
<th>Variable</th>
<th>Individual (J9)</th>
<th>Fully Joint (J1(2))</th>
<th>Fully Joint (J1(3))</th>
<th>Fully Joint (J1(4))</th>
<th>Drop off (J2)</th>
<th>Pick up (J3)</th>
<th>Shared rides (J4)</th>
<th>Joint &amp; Drop (J5)</th>
<th>Joint &amp; Pick (J6)</th>
<th>Joint &amp; Shared (J7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Children aged up to 5</td>
<td>-3.481</td>
<td></td>
<td></td>
<td>0.972</td>
<td>1.487</td>
<td>1.487</td>
<td>1.289</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children aged 6 – 10</td>
<td>-2.964</td>
<td></td>
<td></td>
<td>0.890</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children aged 11 – 15</td>
<td>-1.366</td>
<td></td>
<td></td>
<td>0.686</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Education tour</td>
<td>-0.653</td>
<td></td>
<td></td>
<td>0.593</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance tour</td>
<td>2.621</td>
<td>3.563</td>
<td>1.476</td>
<td>1.457</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Discretionary tour</td>
<td>2.692</td>
<td>4.014</td>
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</tr>
<tr>
<td>Mother of mix aged children (aged 0-5 &amp; 6-16)</td>
<td>0.677</td>
<td></td>
<td></td>
<td>2.685</td>
<td>2.685</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Household w/ 5+ persons</td>
<td>0.181</td>
<td></td>
<td></td>
<td>0.697</td>
<td>0.697</td>
<td>0.697</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>4.446</td>
<td>0.958</td>
<td>-0.060†</td>
<td>0.912</td>
<td>0.813</td>
<td>2.282</td>
<td>0.846</td>
<td>0.896</td>
<td>0.740</td>
<td></td>
</tr>
</tbody>
</table>

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

The results show that as children get older and the need for adult supervision and chauffeuring decreases. This is reflected by decreasing values of the coefficients associated with the children age variables in the utility function of shared rides pattern (J4) on weekdays. This is further confirmed by the negative and decreasing (in magnitude) coefficients of the same variables for individual tour (J9). This trend does not apply to the joint and shared ride pattern (J7) as this tour pattern is dominated by school travel and usually needs two school children to form. For this tour pattern, children aged 6 – 10 years old have the largest coefficient...
estimate, suggesting that they are more likely than children of other age groups to be concurrently escorted to school. The results reflect the different needs and constraints that children at different ages placed on household activity-travel decisions. Vovsha and Petersen (2005) report similar results with older students being more likely to travel independently to school.

The weekend model results (Table 6.5b) offer similar outcomes for children’s travel but on the fully joint tour pattern (J1) as opposed to shared rides (J4). This would fit with serving children tours being directed toward education activities on weekdays while they are leisure-oriented on weekends with leisure activities more likely to be made jointly, as shown in Figure 5.4 (p. 113). Amongst the three age groups, children aged 11 to 15 years old exhibit the most different travel pattern between weekends and weekdays with a much lower need for chauffeuring on weekends. This is unsurprising because they are more independent in their travel and socialising, as compared to younger children.

Maintenance and discretionary activities are, as expected, significantly more likely than work activities (base) to be made jointly by household members. Also, the term ‘the more the merrier’ is clearly reflected in the results with larger coefficients associated with fully joint tour patterns (J1) involving more household members. This is true for both weekday and weekend travel but the trend is clearer on weekends with fully joint tour by four or more persons being considered as a separate joint tour type. Education tours on weekdays have a greater propensity to be served by other household members and individuals making education tours more likely to be a ‘drop off’ than a ‘pick up’. This suggests as school tours and other tours such as work and maintenance can be synchronised more easily for outbound (drop-off) than inbound (pick-up) due to the same location or origin being the home. Education tours are very infrequent on weekends with only 24 observations, and thus estimation with a separate category for education activities did not provide significant parameters. Education and work tours are combined to form activities which are treated as the reference case in the weekend model.

On weekdays, mothers from households with preschool children and pre-driving children (aged 6 – 16) have a significantly greater propensity to make joint drop-off tours (J5), joint pick-up tours (J6), and fully joint tours by three or more household members (J1). In comparison, fathers in households with mixed aged children have an equal propensity to travel individually as their counterparts in households without children of these ages.
(corresponding coefficients are not significant and are removed from the model). Thus, gender differences in household activity-travel arrangements on weekdays are evident, with mothers being primary care givers for children, especially very young ones. Gliebe and Koppelman (2005) report a similar finding in Washington D.C. in terms of discretionary tour making in households with very young children.

Gender differences in household activities allocation still exist over the weekend even though fathers are more likely to be not working. Table 6.5b shows that in households with mixed aged children, fathers and mothers have an equal propensity to make fully joint tours by four or more household members. These are most likely to be to participate in weekend activities involving the entire household. However, in these households fathers are less likely than mothers to involve in fully joint tours by three persons (J1) with a large proportion (44%) of these tours on weekends involving two children and one parent. Compared to weekday patterns, the mothers’ responsibilities on weekends involve more accompanying and less chauffeuring.

Large households (with five or more persons) as expected show a higher propensity to arrange joint tour patterns with a high number of persons involved on weekdays (J1(3), J5, J6 and J7). These households are found to have a higher propensity to take joint tour patterns involving drop-off and pick-up (J2, J3, J5 – J7) which appear to be unpopular choices on weekends. 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. Finally, households where there is the presence of young children (under 15 years old) are more likely than households with older children only or with no children to make fully joint tours by 4 or more household members on weekends. This finding supports Fujii et al. (1999) which concludes that the time spent in joint household activity, particularly with children, is important to individual feelings of satisfaction in daily travel patterns.

6.4.3 Estimation results for the lower model: individual’s mode choice

Parameter estimates for variables affecting individuals’ mode choices for all joint tour patterns are presented in this section. For discussion purposes, the estimation results are organised into several tables and separately for weekday and weekend travel. This section begins with a presentation of individual’s mode choice of different joint tour patterns on weekdays. This is followed by weekend mode choice and its comparison with the weekday
patterns. Using these two models, value of travel time savings are then derived and compared with each other and with international evidence.

**Weekday mode choice**

Coefficient estimates for the variables explaining the individuals’ mode choice of all joint tour patterns on weekdays are shown in Table 6.6 and Table 6.7. At the individual mode choice level, car is treated as the reference mode for each joint tour nest 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. Coefficients associated with the level of service variables (travel times and cost) are well estimated and do not need to be constrained. Value of travel time savings (VOT) can be computed from these parameters and are discussed in the next section. Other variables significantly affecting tour-based mode choices on weekdays include household characteristics, individual characteristics, transport-related fringe benefits, time schedule synchronisation, and land use patterns at both origin and destination.

Household car ownership is shown as a barrier to public transport (PT) use in Table 6.6 with no-car households being more likely than car-owning households to use public transport, 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 (reflected by positive coefficients associated with workers in car-negotiating households for partially joint tours in Table 6.6). This is probably to free the family car for the non-worker in the household to carry out household ‘errands’. This is inferred from the estimation results which show 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). This suggests the limited car availability is the motivation for shared ride arrangements and PT use as a substituting mode to the car. Car-negotiating household members are also found to walk significantly more for mixed joint tour types (J5, J6, and J7) than car-sufficient and no-car household members. A typical example of mixed joint tours by walking on weekdays is that an infant accompanies their mother while she walks their sibling to/from school.
Table 6.6 Estimation results for mode choice of all joint tour types, Sydney average weekday 2007 – 2010*

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Travel cost (2008 AU$), generic</td>
<td>-0.078</td>
<td>-0.078</td>
<td>-0.078</td>
<td>-0.078</td>
<td>-0.078</td>
<td>-0.078</td>
<td>-0.078</td>
<td>-0.078</td>
<td>-0.078</td>
<td>-0.078</td>
</tr>
<tr>
<td>In-vehicle-time (minute), generic</td>
<td>-0.009</td>
<td>-0.009</td>
<td>-0.009</td>
<td>-0.009</td>
<td>-0.009</td>
<td>-0.009</td>
<td>-0.009</td>
<td>-0.009</td>
<td>-0.009</td>
<td>-0.009</td>
</tr>
<tr>
<td>Walk time (minute), generic</td>
<td>-0.020</td>
<td>-0.020</td>
<td>-0.020</td>
<td>-0.020</td>
<td>-0.020</td>
<td>-0.020</td>
<td>-0.020</td>
<td>-0.020</td>
<td>-0.020</td>
<td>-0.020</td>
</tr>
<tr>
<td>Wait time (minute), generic</td>
<td>-0.017</td>
<td>-0.017</td>
<td>-0.017</td>
<td>-0.017</td>
<td>-0.017</td>
<td>-0.017</td>
<td>-0.017</td>
<td>-0.017</td>
<td>-0.017</td>
<td>-0.017</td>
</tr>
<tr>
<td><strong>Public transport</strong></td>
<td></td>
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<tr>
<td>No-car household</td>
<td>1.204</td>
<td>1.065</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Worker in car-negotiating HH</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Household income &gt;AU$67,600</td>
<td>-0.453</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Student over 15 years old</td>
<td>0.257</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Flexible working hours</td>
<td>0.543</td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>PT fare provided</td>
<td>0.602</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Free parking provided</td>
<td>-0.665</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Fuel cost provided</td>
<td>-1.643</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-0.289</td>
<td>-0.907</td>
<td>-1.528</td>
<td>.187‡</td>
<td>.071†</td>
<td>-0.327</td>
<td>-0.306</td>
<td>-2.501</td>
<td>-0.818</td>
<td>.130‡</td>
</tr>
<tr>
<td><strong>Walking</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-car household</td>
<td>1.045</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Car-negotiating household</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Household income &gt;AU$67,600</td>
<td>-0.291</td>
<td></td>
<td></td>
<td>0.392</td>
<td>0.392</td>
<td>0.392</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>0.528</td>
<td>0.816</td>
<td>0.156</td>
<td>1.155</td>
<td>0.958</td>
<td>.007†</td>
<td>0.284</td>
<td>-0.317</td>
<td>-0.612</td>
<td>.138†</td>
</tr>
<tr>
<td><strong>Car</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student over 15 years old</td>
<td>-0.263</td>
<td></td>
<td>-0.263</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Licence holder</td>
<td>0.366</td>
<td>1.173</td>
<td>1.228</td>
<td>-0.256</td>
<td>-0.569</td>
<td>-0.639</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

*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.
Members of high income households are less likely to make fully joint tours by PT. However, they are more likely to make PT tours with shared rides from home but this is low significance. Given that high income households will include a high proportion of dual-earner couples, these results might be expected on weekday activity-travel arrangements because work tours are more likely to be PT-based and mostly independent.

Students over 15 years old exhibit a significantly greater propensity to make PT tours with or without drop-off/pick-up (J9, J3, J4) and a lower propensity to make fully joint car tours (J1), relative to younger students. This might be expected due to their more fixed routines on weekdays, low involvement in childcare, and less reliance on adult household members to participate in individual activities. Having a driving licence increases the propensity of making drop-off tours and pick-up tours (J2 and J3) but decreases the propensity of undertaking both drop-off and pick-up in the same tour (J4 and J7). These results suggest that, 
* ceteris paribus, * licence holders are significantly less likely to undertake both drop-off and pick-up in one car tour and are more likely to return home in between the rides, forming two separate tours.

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 PT fares are provided or if the worker has flexibility at work; conversely, if benefits favour the running of a car with the provision of free parking and/or fuel costs, this significantly reduces the use of PT. The effect of transport-related fringe benefits on the choice of travel mode is significant for individual tours (J9) and, to a lesser extent, drop-off tours (J2).

Table 6.7 shows the coefficient estimates for the variables capturing the effect of land use and the household’s spatial setting. Table 6.7 shows only a subset of joint tour patterns which are significantly influenced by land use characteristics. The mixed opportunities per unit area, capturing both horizontal and vertical mix of land use, 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). But rail kernel density at the origin is largely insignificant on its own in the model without the mixed opportunities per unit area being included as a variable. 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. Commuting tours (work and education) with a longer distance are more likely to involve the use of PT with a drop-off and pick-up being arranged. A more detailed investigation of these commuting journeys reveals that a majority (57%) of drop-offs and pick-ups occur at a public transport node, as opposed to the main activity location (32%).

Table 6.7 Estimation results for weekday mode choice (cont’d): effect of land use patterns

<table>
<thead>
<tr>
<th>Variable</th>
<th>Individual J9</th>
<th>Fully Joint J1(2)</th>
<th>Drop off J2</th>
<th>Pick up J3</th>
<th>Shared rides J4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Public transport</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed opportunities per unit area (‘000s/km²), Destination</td>
<td>0.030</td>
<td>0.021</td>
<td>0.021</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>Distance from home to closest high freq. bus stop (km)</td>
<td>-0.027</td>
<td></td>
<td>-0.102</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance from home to workplace (km)</td>
<td>0.018</td>
<td></td>
<td></td>
<td>0.836</td>
<td></td>
</tr>
<tr>
<td>Distance from home to school (km)</td>
<td>0.019</td>
<td></td>
<td>0.019</td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>Road link density (‘000s/km²), Destination a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.249</td>
</tr>
<tr>
<td><strong>Walking</strong></td>
<td>1.243</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed opportunities per unit area (‘000s/km²), Origin</td>
<td>0.060</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Road link density (‘000s/km²), Origin a</td>
<td>2.605</td>
<td></td>
<td>1.844</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pseudo nodes density (‘000s/km²), Origin b</td>
<td>-0.041</td>
<td></td>
<td>-0.217</td>
<td>-0.247</td>
<td></td>
</tr>
<tr>
<td><strong>Car</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synchronisation of work and school c</td>
<td>0.810</td>
<td></td>
<td>0.816</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detour to work (km) c</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.030</td>
</tr>
</tbody>
</table>

*All parameters are significant at the 5% level or better unless otherwise indicated.

a Measured at the travel zone level; b Measured with the 800 m buffer around the travel zone centroid.

c Applied only to work tours of workers in the household that has at least one student going to school on the same day.

Walking is 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 km²), 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.

Intra-household interactions are again 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).
Weekend mode choice

Table 6.8 shows parameter estimates for variables affecting the tour’s main mode for all joint tour patterns on weekends. As with the weekday model, car is chosen as the reference for each of the joint tour patterns with no constants being specified for car alternatives. The weekend model has fewer explanatory variables than the weekday model because some variables such as commuting distance and flexible working hours are relevant to weekday travel only. Overall, the estimation results for mode choice on weekends are in line with those on weekdays, but there are a number of important differences that can be seen from Table 6.8.

Table 6.8 Estimation results for mode choice of all joint tour patterns, average weekend in Sydney 2007 – 2010

<table>
<thead>
<tr>
<th>Variable</th>
<th>Individual J9, J8</th>
<th>Fully Joint J1(2)</th>
<th>Fully Joint J1(3)</th>
<th>Fully Joint J1 (4*)</th>
<th>Drop off J2</th>
<th>Pick up J3</th>
<th>Shared rides J4</th>
<th>Mixed tour J5-J7</th>
</tr>
</thead>
<tbody>
<tr>
<td>All modes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel cost (AU$)</td>
<td>-0.075</td>
<td>-0.075</td>
<td>-0.075</td>
<td>-0.075</td>
<td>-0.075</td>
<td>-0.075</td>
<td>-0.075</td>
<td>-0.075</td>
</tr>
<tr>
<td>In-vehicle time (minute)</td>
<td>-0.010</td>
<td>-0.010</td>
<td>-0.010</td>
<td>-0.010</td>
<td>-0.010</td>
<td>-0.010</td>
<td>-0.010</td>
<td>-0.010</td>
</tr>
<tr>
<td>Wait time (minute)</td>
<td>-0.019</td>
<td>-0.019</td>
<td>-0.019</td>
<td>-0.019</td>
<td>-0.019</td>
<td>-0.019</td>
<td>-0.019</td>
<td>-0.019</td>
</tr>
<tr>
<td>Walk time (minute)</td>
<td>-0.028</td>
<td>-0.028</td>
<td>-0.028</td>
<td>-0.028</td>
<td>-0.028</td>
<td>-0.028</td>
<td>-0.028</td>
<td>-0.028</td>
</tr>
<tr>
<td>Public transport</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-car household</td>
<td>1.961</td>
<td>1.660</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH income &gt;AU$67.6k</td>
<td>-0.419†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student over 15 years old</td>
<td>0.822</td>
<td></td>
<td></td>
<td></td>
<td>0.570</td>
<td>0.538</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel cost provided</td>
<td>-1.230</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance Home to Bus (km)</td>
<td>-0.186</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rail density, Destn</td>
<td>0.697</td>
<td>0.594</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road link density, Destn</td>
<td>1.421</td>
<td>1.972‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>0.365</td>
<td>-1.420</td>
<td>-1.105</td>
<td>-1.671</td>
<td>-1.027</td>
<td>-0.482</td>
<td>-0.485</td>
<td>-0.219</td>
</tr>
<tr>
<td>Walking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-car household</td>
<td>1.892</td>
<td>1.533</td>
<td>1.749</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car-negotiating household</td>
<td>0.652</td>
<td>0.719</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH income &gt;AU$67.6k</td>
<td>-0.191§</td>
<td>-0.217†</td>
<td>-0.470</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed opportunity density,</td>
<td>0.099</td>
<td>0.142</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Origin</td>
<td>-0.114</td>
<td></td>
<td>-1.317</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>2.397</td>
<td>0.802</td>
<td>0.216†</td>
<td>0.564</td>
<td>1.598</td>
<td>0.333</td>
<td>-0.081†</td>
<td>0.010†</td>
</tr>
<tr>
<td>Car</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-car household</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.487</td>
</tr>
<tr>
<td>Student over 15 years old</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.415</td>
</tr>
<tr>
<td>HH income &gt;AU$67.6k</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.255</td>
</tr>
<tr>
<td>Licence holder</td>
<td>1.939</td>
<td>0.557</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* All parameters are significant at the 5% level or less unless otherwise indicated.
§ Not significant at the 5% level; † Not significant at the 10% level. HH = household. All density measures are in '000s/km².
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 public transport use and walking. No-car households, who are public transport captive users, show a higher propensity to use PT even for fully joint household activities, although it is only significant for a travel party of two. Car-negotiating households walk significantly more than car-sufficient households for joint activities on weekends. In addition, students over 15 years old remain the main public transport users on weekends with or without intra-household drop-offs/pick-ups. They are less likely to be involved 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 public transport use on weekends as with weekdays. Conversely, although the provision of public transport fares significantly increases public transport on weekday travel, it has an insignificant effect on weekend travel and is removed from the model.

Land use patterns still have a significant effect on weekend mode choice with a longer access distance to a good serviced bus stop decreasing PT use as expected. Conversely, good rail coverage and highly connected roads at the destination increase PT use on weekends for fully joint tours (J1) and drop-off tours (J2). Again, rail coverage at the destination appears to have a greater effect on mode choice than rail coverage at the place of residence where difficulties in access can be alleviated with a drop-off. As noted above in the weekday model, rail kernel density is correlated with the mixed opportunity density and so the choice of these two measures should be considered for their theoretical relevance. Rail kernel density at the place of destination is specified for PT mode while the mixed opportunity density is used for walking. This is because rail kernel density describes more directly the condition of PT services on weekends as opposed to the mixed opportunity density measure with some employment categories such as education and health care being closed on weekends. Conversely, the mixed opportunity density is a better proxy for nearby opportunities that can be accessed on foot, and therefore this measure is used to explain walking as the main mode.

This section has interpreted and discussed the behavioural aspects of the estimation results. In this section, the empirical models have been validated in terms of the model fit to the data and the consistency of parameter estimates with expectations. Other important realism tests that should be undertaken during the model development include the values of travel time implied by the model parameters and the sensitivity of the model to changes in key policy variables (Fox, Daly et al., 2009; WebTAG, 2011b). These are discussed in the next sections.
Values of travel time: weekday vs. weekend

The value of travel time (VOT) is one of the most critical parameters for transport modelling and appraisal as this is a critical input into many studies that forecast travel demand and potential revenues for transport projects (Hensher and Goodwin, 2004; Abrantes and Wardman, 2011; KiM, 2013). The values of travel time savings on weekdays and weekends, calculated from the parameter estimates associated with travel times and travel costs in each model, are shown in Table 6.9. In dollar terms in 2008 average prices, in-vehicle time, wait time, and walk time are valued respectively at AU$ 6.77, 12.84, and 15.19 per person hour for weekday travel. These 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, Table 6.9 shows 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 multipliers for wait and walk time, relative to in-vehicle time on weekdays are 1.90 (12.84/6.77) and 2.24 (15.19/6.77). That is, a minute of time spent waiting is valued at 1.90 minutes of on-board time while walking time is valued at 2.24 times higher than on-board time, reflecting the additional discomfort and effort involved. These multipliers are also consistent with international evidence (Kato et al., 2010; Abrantes and Wardman, 2011 among many others).

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; WebTAG, 2011a). A possible explanation for the higher VOTs on weekends is that people have limited time on weekends to participate in joint household activities, recreational and social activities that cannot be done on weekdays (Prasetyo et al., 2003).

Table 6.9 Values of time per person hour (AU$ 2008)

<table>
<thead>
<tr>
<th>Time component</th>
<th>Weekday</th>
<th>Weekend</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-vehicle time</td>
<td>$6.77</td>
<td>$8.09</td>
</tr>
<tr>
<td>Wait time</td>
<td>$12.84</td>
<td>$15.19</td>
</tr>
<tr>
<td>Walk time</td>
<td>$15.19</td>
<td>$22.53</td>
</tr>
</tbody>
</table>
6.5 Policy Analysis

In this section, the empirical models described above are used for policy analysis. A number of hypothetical scenarios are simulated to have a better understanding of the differences between weekday and weekend travel. The estimation results presented in Section 6.4 above have highlighted the key differences between weekday and weekend activity-travel patterns with the determinants of joint household travel arrangements and individual’s choice of travel mode being found to be different over weekdays and weekends. In addition, the value of travel time savings on weekends is found to be higher than that on weekdays. In Chapter 5, weekend and weekday activity-travel patterns have been compared along several dimensions with a specific focus on joint household activities and shared ride arrangements. The results of Chapter 5 show that more than 90 percent 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 weekdays and weekends are associated with different mode shares and hence require different transport management measures aimed to alleviate traffic congestion on weekdays and weekends.

To have more insights into policy implications associated with the differences between weekday and weekend activity-travel patterns, 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 6.10 compares the modal shift on a weekday with that for a weekend day in response to the scenarios of a 50% reduction in public transport fare, a change in travel time, and the introduction of a public transport fare ‘deal’ aiming at group travel. The first scenario is chosen due to its simplicity with the extent of the fare reduction being arbitrary while the latter two scenarios are used to demonstrate the capacity of joint travel analysis. 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 public transport 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 public transport 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).

Table 6.10 Estimation of modal shifts in response to same scenarios on weekday and weekend

<table>
<thead>
<tr>
<th>Modal shift</th>
<th>-50% PT fare</th>
<th>Change in travel time</th>
<th>PT fare deal†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weekday</td>
<td>Weekend</td>
<td>Weekday</td>
</tr>
<tr>
<td>Car</td>
<td>-2.5%</td>
<td>-0.9%</td>
<td>-1.8%</td>
</tr>
<tr>
<td>PT</td>
<td>2.7%</td>
<td>1.0%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Walking</td>
<td>-0.2%</td>
<td>-0.1%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

†Applied to group travel only.

With a simple reduction of public transport fares, a higher modal shift from car to public transport is predicted for weekdays as compared to weekends. This is expected as weekend travel is characterised by a higher proportion of fully joint household travel (46% on weekends vs. 21% on weekdays) with people preferring to travel by car as the marginal cost per person are lower than using public transport 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. This is because there is more individual travel on weekdays, and thus, the target population affected by these policy changes has a proportionately bigger impact. Similarly, public transport 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 reduction 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 public transport group fare deal is quantitatively smaller. However, this might be expected from the lower frequency of Sydney public transport 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. Also, considering that PT level of services are much lower on weekends with weekend PT share being half of that on weekdays, the
impact of the group fare deal on weekend modal shift relative to that on weekdays is greater than their absolute difference would appear.

With a noticeable proportion of regional travel being made jointly by household members, explicitly analysing and modelling joint household travel has great potential for improving travel demand forecasting and policy analysis. For example, with the same policy aiming at group travel such as the introduction of HOT/HOV lanes and public transport group fare ‘deals’, the above scenario analysis shows that the former is more successful on weekdays and the latter on weekends. The simulation analysis not only shows how joint household travel contributes to these differences but also highlights the advantages of a joint household travel analysis over an individual travel analysis, which simply does not have the capability of simulating the effect of such policies on travel behaviour. Although mode choice models that do not distinguish joint tours from individual travel are able to analyse transport policy such as a PT fare reduction, the modal shift might be significantly mis-estimated. This is because in such models, the mode choice decision is solely attributed to the level of services with the synchronisation of household members’ activities and the opportunities for joint travel being ignored (Vovsha et al., 2003). The next section investigates this difference in more detail where a mode choice model without a joint travel dimension is developed to undertake a parallel analysis.

### 6.6 Parallel Analysis

Using the weekday model and the three-step simulation procedure described above, Figure 6.4 shows the contribution of all tour types to the aggregated modal shift resulting from a variety of scenarios. The scenarios used for a parallel analysis include the abovementioned 50% reduction in PT fare (-50% PT fare), a 20% cut of in-vehicle time for PT (-20% PT time), providing all workers with PT fares (Fare provided), taking away free parking lots at the workplace (No free parking), or allowing all workers to have flexible work hours (Flex hours). The parallel analysis cannot use the simulation results of the introduction of HOV/HOT lanes and PT fare ‘deals’ for group travel because these changes cannot be simulated in an adopted mode choice model without a joint travel dimension.

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5 This section is based on a research published in Ho (2013) which was awarded the Innovation Grant from the World Conference on Transport Research held in Rio de Janeiro, Brazil in July 2013.
Figure 6.4 shows for all scenarios, individual tours contribute the most while tours involving fully joint travel (i.e., fully joint and mixed tours) contribute the least to the modal shift. This finding is expected as using a household car for joint household travel is still cheaper than using PT so the benefit of a 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 6.4 Estimated modal shift on weekday for changes to policies and level of services](image)

Given the substantial differences between individual and joint travel responses to the scenarios shown in Figure 6.4, 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 (Ben-Akiva and Morikawa, 1990; Hensher and Bradley, 1993; Ortuzar and Iacobelli, 1998). This technique, which is a common practice in estimation of RP – SP choice models, provides a means of accommodating differences in scale between datasets (tours of different purposes) and combining them in a single empirical model. This makes the mode choice model without a joint travel dimension not only consistent with the activity-based modelling framework (Bradley and Bowman, 2006; Davidson et al., 2007) but also more effective in simulation. Table 6.11 shows the estimation results of the weekday mode choice model without a joint household travel dimension.
Table 6.11 Estimation results (t-stat) of tour-based mode choice model without joint household travel dimension for different travel purposes, Sydney average weekday

<table>
<thead>
<tr>
<th>Variable</th>
<th>Work</th>
<th>Education</th>
<th>Maintenance</th>
<th>Discretionary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel cost (2008 AUS), generic</td>
<td>-0.093 (-32.47)</td>
<td>-0.093 (-32.47)</td>
<td>-0.093 (-32.47)</td>
<td>-0.093 (-32.47)</td>
</tr>
<tr>
<td>Travel time (minute), generic</td>
<td>-0.014 (-9.99)</td>
<td>-0.014 (-9.99)</td>
<td>-0.014 (-9.99)</td>
<td>-0.014 (-9.99)</td>
</tr>
<tr>
<td>Wait time (minute), generic</td>
<td>-0.028 (-17.17)</td>
<td>-0.028 (-17.17)</td>
<td>-0.028 (-17.17)</td>
<td>-0.028 (-17.17)</td>
</tr>
<tr>
<td>Walk time (minute), generic</td>
<td>-0.059 (-16.66)</td>
<td>-0.059 (-16.66)</td>
<td>-0.059 (-16.66)</td>
<td>-0.059 (-16.66)</td>
</tr>
<tr>
<td><strong>Public transport</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-car household</td>
<td>1.802 (9.22)</td>
<td>0.769 (3.72)</td>
<td>2.450 (10.55)</td>
<td>2.452 (6.31)</td>
</tr>
<tr>
<td>Car-negotiating household</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worker</td>
<td>0.279 (2.26)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-worker</td>
<td></td>
<td></td>
<td>0.175 (0.22)</td>
<td></td>
</tr>
<tr>
<td>No. of pre-driving children</td>
<td>-0.225 (-3.06)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worker</td>
<td></td>
<td></td>
<td>-0.626 (-2.15)</td>
<td></td>
</tr>
<tr>
<td>Non-worker</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel party size</td>
<td>-0.105 (-2.11)</td>
<td>-0.340 (-3.36)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of children under 5 years old</td>
<td>-0.208 (-1.66)</td>
<td>-0.297 (-1.81)</td>
<td>-1.167 (-3.32)</td>
<td></td>
</tr>
<tr>
<td>Household income &gt; $AU 67,600</td>
<td>-0.784 (-5.06)</td>
<td>-0.402 (-1.57)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexible work hours</td>
<td>0.618 (1.83)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PT fare provided</td>
<td>1.414 (4.59)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free parking provided</td>
<td>-1.110 (-8.19)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel cost provided</td>
<td>-2.788 (-13.7)</td>
<td>-3.278 (-6.06)</td>
<td>-1.296 (-1.89)</td>
<td></td>
</tr>
<tr>
<td>MPSD</td>
<td>0.345 (3.71)</td>
<td>-0.111 (-0.70)</td>
<td>0.864 (7.58)</td>
<td>0.971 (3.89)</td>
</tr>
<tr>
<td>MPMD</td>
<td>-0.263 (-3.09)</td>
<td>0.013 (0.12)</td>
<td>-0.240 (-2.17)</td>
<td>-0.055 (-0.29)</td>
</tr>
<tr>
<td>Distance: home – freq. bus stop (km)†</td>
<td>-0.036 (-1.40)</td>
<td></td>
<td></td>
<td>-0.209 (-1.85)</td>
</tr>
<tr>
<td>Student aged 6 – 10 years old</td>
<td>1.018 (7.34)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student over 15 years old</td>
<td>0.637 (4.52)</td>
<td></td>
<td>1.547 (5.16)</td>
<td></td>
</tr>
<tr>
<td>Distance: home-school (km)</td>
<td>0.010 (2.57)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance: school-bus stop (km)</td>
<td>-0.010 (-3.17)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance: home-school over 2 km</td>
<td>1.648 (8.28)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rail kernel density, Destination</td>
<td>0.913 (9.50)</td>
<td>0.955 (5.59)</td>
<td>1.142 (6.10)</td>
<td>2.175 (9.19)</td>
</tr>
<tr>
<td>Mixed opp. density (‘000s/km²), Destn</td>
<td>0.027 (5.88)</td>
<td>0.037 (4.16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-0.447 (-4.20)</td>
<td>-1.758 (-7.03)</td>
<td>-1.023 (-4.67)</td>
<td>-2.306 (-6.98)</td>
</tr>
</tbody>
</table>

† High frequency serviced bus stops are defined as having 12 or more services per hour in the am-peak.
Table 6.11 (Continued) Estimation results (t-stat) of tour-based mode choice model without joint household travel dimension for different travel purposes, Sydney average weekday

<table>
<thead>
<tr>
<th>Variable</th>
<th>Work</th>
<th>Education</th>
<th>Maintenance</th>
<th>Discretionary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-car household</td>
<td>2.489 (8.81)</td>
<td>1.24 (5.30)</td>
<td>1.849 (10.54)</td>
<td>1.472 (5.25)</td>
</tr>
<tr>
<td>Car-negotiating household</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worker</td>
<td>0.392 (1.47)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexible work hours</td>
<td>1.998 (2.13)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPSD</td>
<td>1.469 (7.06)</td>
<td>1.340 (10.44)</td>
<td>1.505 (5.56)</td>
<td></td>
</tr>
<tr>
<td>MPMD</td>
<td>-0.937 (-3.30)</td>
<td>-0.930 (-6.56)</td>
<td>-1.942 (-5.83)</td>
<td></td>
</tr>
<tr>
<td>Student aged 6 – 10 years old</td>
<td></td>
<td>1.135 (6.68)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student over 15 years old</td>
<td></td>
<td>1.610 (8.01)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance: home – work under 2 km</td>
<td>1.642 (6.24)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance: home – school under 1 km</td>
<td></td>
<td>0.449 (2.78)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed opp. density ('000s/km$^2$), Destn</td>
<td>0.081 (10.06)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed opp. density ('000s/km$^2$), Origin</td>
<td></td>
<td>0.110 (3.89)</td>
<td>0.127 (2.35)</td>
<td></td>
</tr>
<tr>
<td>Road link density ('000s/km$^2$), Origin</td>
<td></td>
<td>3.532 (6.66)</td>
<td>4.568 (4.96)</td>
<td></td>
</tr>
<tr>
<td>Pseudo node density ('000s/km$^2$), Origin</td>
<td></td>
<td>-0.079 (-1.94)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-0.060 (-0.17)</td>
<td>0.394 (2.36)</td>
<td>0.760 (5.40)</td>
<td>1.029 (4.31)</td>
</tr>
<tr>
<td>Inclusive value parameter</td>
<td>1 (fixed)</td>
<td>0.809 (3.34)</td>
<td>0.916 (1.44)</td>
<td>1.318 (-3.32)</td>
</tr>
<tr>
<td>Scale factor</td>
<td>1 (fixed)</td>
<td>1.236 (3.34)</td>
<td>1.091 (1.44)</td>
<td>0.759 (-3.32)</td>
</tr>
<tr>
<td>Number of observations</td>
<td>16,522</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of parameters</td>
<td>84</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log likelihood at convergence</td>
<td>-6,402</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pseudo adjusted R-squared (const)</td>
<td>0.366</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* t-values against one are calculated for inclusive value parameters and scale factors. Other t-values are compared against zero.

Work tours are chosen as the reference with its IV parameter being set to one while the IV parameters for the education, maintenance and discretionary tours are estimated freely. The IV parameters do not have to lie between zero and one which is used as a condition for consistency with random utility maximisation because the alternatives in one dataset are not available observations in other datasets (Hensher and Bradley, 1993). The scales of the education and maintenance datasets (equal to the inverse of the corresponding IV parameter) are larger than one, suggesting that these datasets have more noise than the home-based work tour dataset, although the difference is not significant for maintenance tours (Ortuzar and...
Iacobelli, 1998). A similar interpretation can be drawn for the discretionary dataset which contain less noise than work tours. McFadden’s adjusted Rho-squared is 0.366 indicating a relatively good fit to the data. Overall, this model delivers all parameters of the expected sign. Rather than interpreting the estimation results of this model in detail, the following discussion highlights the results which are more relevant to the parallel analysis, which is the main purpose of this section.

The model without a joint travel dimension treats travel times and travel cost as generic across alternatives, as with the model with joint household travel. The estimated VOTs on weekdays in 2008 prices for in-vehicle, wait and walk times are AU$ 9.03, 18.06, and 38.06 respectively. These VOTs are higher than those obtained from the model with joint household travel shown in Table 6.9 above. This is because the model without a joint travel dimension could not see the benefits of using a car over the PT for joint travel, especially in terms of travel cost. As a result, the impact of the travel cost on mode choice decisions may be underestimated which in turn results in higher VOTs.

The effect of intra-household interactions on mode choice is indirectly captured in the model without joint household travel through its introduction of the travel party size and the allocation of household resources (car, drivers) and tasks (chauffeuring) in car-negotiating households. Table 6.11 shows that workers in car-negotiating households use public transport significantly more than workers in car-sufficient households (base) whereas non-workers in car-negotiating households use the car as much as their counterparts in car-sufficient household. This is consistent with the outcomes of the model with joint household travel which suggests that workers in car-negotiating households may commute by PT to free the family car non-workers running household errands. Intra-household interactions are also evident in the effect of the presence of pre-driving age children on the travel arrangements of workers and non-workers in a household. Workers in households with pre-driving age children have a significantly greater propensity to commute by car, relative to workers in households without pre-driving age children. This suggests workers with school-age children take the opportunity to combine commuting with chauffeuring children to/from school, a household task which otherwise separately undertaken by a non-worker as a maintenance tour. In addition, the propensity of public transport use decreases as travel party size increases, reflecting the demand for a household car and intra-household interactions in mode choice for joint household travel. Again, these results are consistent with joint travel analysis and suggest that the developed model is reasonable for a parallel analysis.
Table 6.12 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 would produce a higher modal shift (Vovsha et al., 2003; Bhat et al., 2012; Gupta and Vovsha, 2013). However, two reasons may 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 6.12. 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 6.12 Estimation of modal shifts for different scenarios using weekday models with and without joint household travel (without joint household travel in round brackets)

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

* Values in square parentheses are base market shares on weekdays of the corresponding mode.

† The effects of the free parking and flexible working hours on commuting mode choice are significant only for individual (J9) and drop-off (J2) tours. Thus, mode choices of other tour types are not impacted by the policy.
6.7 Summary of Estimation Results

The typology of tour allows various patterns of joint household activities and shared ride arrangements to be embedded in the model structure which appears to explain the motivation and constraints on individual choices of joint travel patterns and main travel modes. The model fit statistics, inclusive value parameters, coefficient estimates, and value of travel time savings demonstrate the validity of the modelling approach. In the results, the inclusive value parameters were well estimated and did not need to be constrained, supporting the natural structure of decisions underpinning the model. Second, the model results are consistent with expectations from an activity-based travel behaviour viewpoint where travel is considered as being derived from the demand for activity participation. Third, as discussed, the parameter estimates are behaviourally meaningful. Fourth, the value of travel time savings are consistent with empirical evidence from Australia and, the implied multipliers of walk and wait times relative to in-vehicle time are in line with international evidence. These pieces of evidence collectively lend support for the modelling approach adopted in this research which assumes activity generation and joint travel arrangement precede mode choice.

In terms of interpretation, the results presented in this chapter provide evidence of intra-household interactions in the travel mode choice of each household member and highlight factors associated with joint household activities and shared ride arrangements, with a distinction between weekdays and weekends. The results show that weekend travel is directed towards maintenance and recreation/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. Whilst these differences exist in the arrangement of joint household activity-travel between weekdays and weekends, some consistent patterns also emerge that suggest four main drivers: household resources, social and mobility constraints, spatial setting, and situational factors.

In terms of intra-household shared ride arrangements, the significant parameter estimates of household car ownership, driving licence and household size suggest that the availability of a household car and the opportunity for joint travel play an important role in the arrangement of household activity and travel. Ceteris paribus, workers in car-negotiating households are found to use public transport significantly more than their counterparts in car-sufficient households but this positive effect is conditioned by the arrangement of a drop-off/pick-up, most likely at a public transport node. In contrast, having fewer cars than household drivers
(i.e. car-negotiating household) does not exhibit any significant difference in car use of the non-worker, as compared to their counterpart in car-negotiating households. Commuting patterns tend to be simple in Sydney with long working hours in between and this may lead to the decision of car-negotiating households to regard the efficient use of car resources as using drop-off and/or pick-up for the worker so as to free the family car for the non-worker to run household errands. This is further reinforced with the evidently unpopular choice of drop-off and pick-up arrangements on weekends with only large households showing a tendency to undertake the joint tour patterns involving a drop-off/pick-up. This reflects the higher opportunity to coordinate joint travel in the form of shared rides when there are more people in a household.

A second factor that motivates and constrains joint household travel is the presence of children and their ages. The estimation results clearly show that under social and mobility constraints associated with the presence of children, especially very young ones, parents need to specialise in their roles and organize joint household travel to fulfil household and individual needs. The impact of children on joint household travel arrangements arises from the need for adult supervision and chauffeuring, and these requirements vary across children’s ages. Very young children require constant adult supervision and care and the estimation results reveal that they are most likely to join in with adult household members when these persons provide drop-offs and pick-ups to other household members. School-age children need less supervision but more escorts to and from school on weekdays and children’s mobility demand is likely to be met by mothers if preschool age children are also present in the household. On weekends when fathers are more likely to be not working, gender-based roles still exist. The estimation results suggest that fathers in households with mixed aged children are less likely than mothers to participate in fully joint tours by three persons, with a noticeable proportion (65% on weekdays and 44% on weekends) of these tours involving one parent and two children.

The estimation results indicate that the household’s spatial setting and land use patterns at both origin and destination significantly contribute to the relative utility of the specific travel modes and joint tour patterns. Significant positive coefficient estimates for commuting distance suggest that workers and students with spatial separation in distance between home and workplace/school prefer to commute by public transport with a drop-off and/or a pick-up being arranged. In addition, the mode choices arising from different joint tour patterns are found to be influenced by access to good public transport services, street layout and mix of
opportunities. Also, land use patterns at the place of destination appear to be more important for PT users than those at their place of residence where access to PT services can be done by kiss and ride or park and ride.

When the household’s spatial setting is considered, having flexible working hours and time schedule synchronisation between household members are additional determinants of whether out-of-home activities are accessed jointly or individually. The estimation results show that workers where work and school times are synchronised are more likely to commute by car and combine commuting with chauffeuring students to/from school, a household task which otherwise separately undertaken by a non-worker as a maintenance tour. However, a workers’ propensity to drop-off students at school en route to work decreases as the detour distance due to serving students increases. The results also indicate that having transport-related fringe benefits significantly contributes to the worker’s decision of being a car commuter or a PT user, depending on whether the benefits provided to the worker from their employer favour the running of a car or the use of PT.

To demonstrate the practical relevance of the estimation results, the value of travel time savings are derived and ‘what if’ scenarios are performed for both weekday and weekend travel. The VOTs are found to be higher on weekends than on weekdays, which is counter to the common belief that weekend VOTs are lower than weekday VOTs although not without international evidence. This finding alongside the difference in proportion of joint travel between weekdays and weekends has been shown through scenario analysis to have important implications for travel demand management and policy formulation such as those relate to HOV/HOT lanes and discount PT fare tickets for group travel. The implications are discussed further in the next chapter. Finally, parallel analysis has demonstrated the differences that interpersonal interactions make to implications for transport policy, as compared to individual travel analysis.

All in all, the estimation results discussed in this chapter show that the typology of joint household tour patterns developed for this study is effective in integrating intra-household interactions with individual tour-based mode choice. Using this tour typology, two empirical models were developed to fully test the four hypotheses identified in Section 2.6. Overall, the estimation and simulation results presented in this chapter provide not only strong evidence supporting these four hypotheses but also important insights into policy formulation and
planning practices. Chapter 7 summarises the hypothesis testing results and discusses their implications in detail.
CHAPTER 7. FINDINGS AND CONCLUSIONS

Chapter 1 and Chapter 2 describe the research objectives of this thesis and its associated hypotheses. Chapter 3 through to Chapter 6 present the works conducted to obtain the research objectives and to test the research hypotheses. This final chapter summarises the research findings and highlights the original contributions of this thesis as well as its limitations. The chapter opens with a summary of joint household travel, the main topic of this thesis, from both theoretical and practical perspectives and is oriented towards a discussion on the extent to which the research objectives have been met. Then, the results of the hypothesis testing are discussed alongside their implications for travel demand modelling and policy formulation. Finally, the key contributions of this thesis are summarised and some areas for future research are suggested.

7.1 Overview of Joint Household Travel

The theoretical underpinning of this thesis posited that travel arises from the demand for activity participation, and that the travel decisions of a household member are not necessarily independent of the travel behaviour of other members of their household. 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. In addition, joint household travel, especially for shared activities, may be driven by the added utility of joint participation in the same activity. From this basis, this study hypothesised that individual choices of travel mode are likely to be constrained by joint household travel decisions. In addition, households with different resource constraints and spatial settings are hypothesised to have different allocations of household resources and arrangements of household activities and travel. For example, the limited availability of a household car may motivate the use of car resources by arranging a drop-off and/or a pick-up for the worker so as to free the family car for the non-worker to run household errands. This travel arrangement might be even more likely if the workplace is in a close proximity to a public transport service, in a good walking environment and/or an area where land use is mixed that allows workers to access non-work activities without a need for a car. This example embodies another hypothesis of this study which is that joint household travel arrangements are different on weekend days when work and school activities are less likely to occur. Weekend travel tends to be oriented towards social and leisure activities which are of more relaxed and social in nature and are more likely to be characterised by a high share of joint participation. Differences in household activities
and joint household travel between weekdays and weekends if demonstrated have different implications for transport policy formulation.

The empirical portion of this study used the 3-year pooled Sydney HTS data and focussed on the identification of joint household travel patterns and an analytical approach to modelling individual tour-based mode choices with joint household travel arrangements. The research identified joint household tours as patterns of intra-household interactions and spatial-temporal constraints where a home-based tour is used as the unit of analysis and is defined as a sequence of trips starting and ending at the individual’s home. Using flexibly defined matching criteria and a 2-staged approach, this study identified nine joint tour patterns, representing nine different ways of arranging household activities and travel into a home-based tour. Apart from the fully joint tour and individual tour patterns, which are the two most common patterns in daily travel, the other seven joint tour patterns include partial joint tours and mixed tours. The four partially joint tour patterns were distinguished from each other by the sequence of joint trip or trips in a home-based tour. Whether these joint trips are arranged at the beginning of a tour (drop-off) or at the end of the tour (pick-up) or both (shared rides) or in the middle of the tour (joint in middle) had different implications for intra-household interactions and spatial-temporal constraints. The remaining three mixed joint tour patterns were differentiated from each other by the combination of a fully joint tour with one of the partially joint tours (drop-off, pick-up, or shared rides). The joint in middle tour pattern was found to be relative rare in the Sydney dataset, making it a poor candidate for combining with other joint tour types in defining mixed tour patterns.

Using the typology of joint household tours, the research developed a modelling approach which explicitly incorporated intra-household interactions in travel model choice through the individual choice of joint tour patterns that embody the household members’ agreement upon time and space constraints for the journey. The model structure took the form of a nested logit model of two levels, with each level being applied for the tour decision. In the upper level, household members were regarded as having matched their activity agendas so as to identify the needs for, and the possibilities of, travelling together for the entire tour or for some trip segments of the tour. The lower level represented the individual’s choice of main travel mode contingent on their choice of joint tour patterns. With this modelling approach, the individual choices of joint travel patterns and travel modes were modelled simultaneously with the individual being treated as the decision-making unit. Two models, one for weekday and one
for weekend, are estimated in this research using the empirical data constructed from the Sydney HTS data.

The empirical results show that this model structure is consistent with the utility maximising theory and activity-based travel behaviour where travel is considered as being derived from the demand for activity participation. A wide range of explanatory variables are used in the model including household and individual characteristics, tour attributes, land use patterns at both origin and destination, spatial and temporal synchronisation of household members’ activities, and transport-related fringe benefits provided to the worker. The estimation results form the basis of discussion as to the extent to which the research objectives of this study, described in Section 1.1, and its associated research hypothesis, described in Section 2.6, have been met. These are discussed in the next section.

7.2 Empirical Findings and Implications for Modelling and Policy Formulation

In very broad terms, the research objectives of this study have been met with a deeper understanding of the impact of joint household travel on individual mode choice behaviour being obtained. In addition, strong evidence has been found in this study that provides valuable inputs into transport policy formulation and planning practice. These are discussed in relation to the four research hypotheses identified in Chapter 2. The results of each hypothesis test are discussed first in the light of the extent to which it has been met, followed by implications for travel demand modelling and policy formulation.

Hypothesis 1. *Household interactions underlie observed individual travel mode choice and are affected by household context, choice situation, and social and mobility constraints.*

Intra-household interactions in individual travel mode choice are evidenced by the prevalence of joint household travel and the differences in mode choice behaviour across joint tour patterns. The descriptive analysis provided in Chapter 5 showed that joint household travel accounts for a substantial proportion of regional travel demand. Using different units of analysis including trip, home-based tour, and daily activity-travel pattern, the comparison of joint household travel across countries revealed a number of similarities internationally in terms of joint household travel. Also, the percentage of regional travel which was made jointly was shown to differ substantially when different units of analyses were used. Joint household travel accounted for about 20% of total trips and about 50% of total home-based
tours on weekdays, with weekend joint travel being found to be higher. In addition, modal shares were shown to split differently across joint tour patterns with fully joint tours being less likely than individual and partially joint tours to be PT-based. However, these descriptive statistics are indicators of the influence of joint household travel on the individual choice of travel mode as the descriptive analysis does not incorporate the influence of other factors such as the level of service and the synchronisation of activities of different household members, nor the direction of causation. These have been addressed in the modelling analysis described next.

The modelling approach, developed in Chapter 6 at the individual level where the choice of tour main mode was formulated conditional on the choice of joint tour patterns, was supported by the empirical data, the utility maximising theory, and the premise of activity-based travel behaviour. The estimation results suggested different determinants of travel mode choice for different joint tour patterns with transport-related fringe benefits, for example, having a strong impact on mode choice of individual tours but not joint tours. This suggests the relevance of the analysis of joint household travel not only for a better understanding of travel behaviour but also for improved travel demand forecasting and policy analysis.

The models for weekday and weekend travel estimated in Chapter 6 suggest that interactions within households are an important motivation and provide constraints on the individual choices which lead to observed joint tour patterns and main travel modes. Joint household activities and shared ride arrangements were found to be influenced by household context (i.e., the unavailability of household cars for all household drivers, number of persons in the household, and household type), social and mobility constraints (i.e., very young children who neither stay home alone nor travel independently), the household’s spatial setting (i.e., access to good public transport service and local facilities, spatial separation between home, work and school) and situational factors such as travel purpose and time schedule synchronisation of household members’ activities. In addition, mode choices of different joint tour patterns were found to be influenced by household and individual characteristics, travel times and costs, and transport-related fringe benefits provided to the worker.

Thus, hypothesis 1 has been fully met in this study through the descriptive statistics and modelling process. Apart from providing evident supporting this research hypothesis, the modelling results have important implications for policy formulation and planning practices which are discussed next.
The significant impact of transport-related fringe benefits on mode choice of some but not all joint tour patterns have policy implications, in particular an assessment of policies for increasing public transport use by improving the level of public transport services or encouraging public transport use through the provision of financial incentives by commuters’ employers. For example, while the provision of PT fares to workers is found to increase significantly their PT use for individual tours, this effect is not significant for any tour pattern involving joint household travel. This means that employer-based policies aiming to increase PT use for commuting journeys through financial incentives will not significantly move workers out of their cars if they have to drop-off/pick-up their children en route to/from work. In addition, the effect on weekend PT use is insignificant for the provision of PT fares while remains significantly negative for fuel costs. This suggests that the provision of fuel costs remains a significant barrier to PT use on weekends as with weekdays.

The results from this study emphasize the importance of segmenting travellers and implementing transport policies accordingly. For instance, the results indicate that education is most likely to be served in both directions, and that household chauffeurs are more likely to return home in between the rides, forming two separate home-based tours. These tours are also most likely to be made by car during peak hours, adding to the environmental burden and traffic congestion. Considering that school travel is regular in terms of fixed times, days and locations and the chauffeur usually has no purpose other than serving the passengers, these findings suggest a targeted market for changing mode from car to PT. Improved school bus services may address the need of chauffeuring children to school, although it must be acknowledged that other factors may influence the choice to escort children to school, including children characteristics and parent attitudes to child safety (Vovsha and Petersen, 2005; Wen et al., 2008; Yarlagadda and Srinivasan, 2008b; Sidharthan et al., 2011).

**Hypothesis 2.** Travel mode choices of different joint household travel arrangements are influenced by land use characteristics measured at a micro-level such as:

- Proximity to public transport (Origin and Destination).
- Degree of mixed land use (Origin and Destination).
- Activity density (Origin and Destination).
- Aspects of network design and layout (Origin and Destination).
The land use patterns at both origin and destination were found to have a significant impact on the mode choices arising from different joint tour patterns. The proximity to public transport services is captured by walking distance from home, school, and work place to the nearest (high frequency) bus stop as well as rail kernel density at both origin and destination. Not all of these PT proximity measures were significant but the estimation results showed the importance of having a high frequency serviced bus stop close to home and good rail coverage at the destination. The mixed land use measure appeared to have an insignificant direct effect on tour-based mode choice when used on its own but a highly significant impact when combined with activity density to define a combined measure of mixed opportunity density, which captures both horizontal and vertical mix of land use. The estimation results confirmed that aspects of the street design and layout, characterised by street density and pseudo node density, significantly influence walking and PT use for a number of joint tour patterns. These results provide evidence supporting hypothesis 2 but it is acknowledged that the strength of evidence depends on which variables are chosen to measure the land use patterns. This is discussed further in Section 7.4.

The use of a micro-level approach from an intra-household interaction perspective for the investigation of land use in this study has offered additional evidence to support transport policies and planning practices that are typically built on micro-level evidence. Amongst various aspects of land use introduced in the model, the rail kernel density at the main destination and access to a high frequency serviced bus stop from home showed a strong influence on mode choice, mainly for the individual and partially joint tour patterns. However, the rail kernel density at the place of residence was largely insignificant. These findings suggest that providing good rail coverage to key destinations may have a larger impact on PT use than good rail coverage at the place of residence where access to rail service can be done by K&R or P&R. In addition, the rail kernel density measure was highly correlated with the mixed opportunity density and therefore captures these impacts too. Also, tours involving multiple purposes at a single destination were more likely to be PT oriented. Together, this suggests that planning strategies to increase PT use need to focus on providing multiple activities at a single destination, supported by a good rail service. For instance, a cluster of activity centres where people can do social/recreational, shopping and personal business at one place without the need to travel in between by motorised modes could promote PT use. Also, increased mixed land use developments at workplaces to allow workers to do multiple activities near their workplaces would reduce car commutes. The empirical results suggest this effect is stronger if a connected walking environment exists or is
created which in turn allows tours with multiple activities at a single destination to be made. With respect to the place of residence, having a high frequency serviced bus stop close to home seems to increase PT use, but mainly for individual travel, while a good mix of opportunities and an pedestrian-friendly design of street networks appear to encourage walking.

Hypothesis 3. Weekend travel is significantly different from weekday travel in terms of joint household travel arrangements and shared activities.

By separating weekend activity-travel from their weekday counterparts, this study has been able to quantify differences using data from the 3-years pooled Sydney HTS. Weekend and weekday activity-travel patterns were compared along several dimensions with a specific focus on joint household activities and shared ride arrangements. The results showed a difference between weekday and weekend travel with the latter being directed towards maintenance and recreation/social activities and characterised by a higher joint household activity participation rate. In contrast, weekday travel was found to be more oriented to work and education-related activities and distinguished by more intra-household shared ride arrangements. With respect to shared activities chained into joint tours, the results show a higher occurrence rate and a longer activity duration on weekends than on weekdays. These findings strongly support hypothesis 3.

The differences in household activities and travel patterns over weekends and weekdays are also reflected in different mode shares and will require different transport management measures to alleviate traffic congestion. For instance, ceteris paribus, the same reduction of public transport fares was identified, using the scenario analysis, to result in a lower modal shift from car to public transport on weekends than on weekdays. Joint household travel is likely to be cheaper per person by car than public transport 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. This increased understanding of the differences between weekday and weekend travel is useful for policy-making related to, for example, the introduction of high occupancy vehicle/toll lanes or public transport group fare ‘deals’ with the former being shown to be more successful on weekdays and the latter on weekends.
Hypothesis 4. Joint household travel analysis identifies different modal shifts for policy outcomes, as compared to individual travel analysis.

The parallel analysis investigated in Section 6.6 has highlighted the benefits of studying joint household travel and has provided evidence to support hypothesis 4. The simulation outcomes consistently indicated that for the same scenario, the model without joint household travel identifies different modal shifts as compared to the model with joint travel dimension. In total, five scenarios were used for this comparison, including a reduction of PT fare, a reduction in PT travel time, providing all workers with PT fares, removal of free parking at the work place, and allowing all workers to have flexible working hours. The simulation outcomes for these scenarios lead to the consistent conclusion including joint household travel gives a different modal shift as compared to individual travel analysis. The better behavioural underpinning of the model with joint household travel together with evidence on intra-household interactions provided in this thesis allows a joint travel analysis to be considered superior than an individual travel analysis, although both models have expected parameter estimates and reasonable goodness of fit which cannot be used to compare models (Hu et al., 2006).

The substantial difference between individual and joint travel in response to all scenarios provides insights into the potential limitations of PT strategies designed by planners and policy-makers. For a scenario with lower fares for PT, for example, a model incorporating joint household travel as developed in this study shows a different modal shift from car to PT as compared to a model without joint household travel. Scenario analysis shows that individual tours contribute the most while joint and mixed tours contribute least to modal shifts from car to PT, suggesting that using a household car for joint household travel is cheaper than using PT for group travel so the effect of the lower fare policy on PT use accrues only to individual travellers. This shows the importance of including intra-household interactions into travel demand models since without these interactions, the lower fare policy would see the car mode becoming relatively more expensive than the PT mode for all travel (both individual and joint), resulting in an unrealistic modal shift to PT from car.

7.3 Contributions of this Research
This thesis has examined joint household travel arrangements and their mode choice. The study has offered 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.
This research has made three broad contributions. First, a systematic typology of joint household tours has been developed that is effective in differentiating tours based on tour structure and the implied intra-household interactions. This disaggregate allows more insights to be gained following estimation. Second, joint household activity and travel patterns for both weekdays and weekends have been analysed to provide understanding in the difference between weekday and weekend in terms of joint travel, shared activities and associated implications for transport policy. Third, the parallel analysis has deepened the understanding of the impact of joint household travel on travel demand forecasting. The areas in which this thesis has contributed are highlighted next.

The empirical model has contributed to the growing literature on modelling intra-household interactions, an essential element in advanced activity-based models. First, the model considered joint activity-travel patterns amongst all household members and not just between household heads or between parents and children. In addition, various patterns of intra-household interactions in daily travel under social, temporal and spatial constraints were effectively captured by the typology of joint household tour patterns embedded in the model, avoiding unnecessary assumptions employed by previous approaches such as serving household passengers’ travel is by car only and is allocated directly to the passenger’s activity. Also, the systematic typology of joint tours can be extended to consider additional dimensions of the tour such as activity type and tour complexity. Finally, by modelling the individual choice of joint tour pattern and mode choice at the tour level, this study has added 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, joint activity participation, and allocation of maintenance activities among household members (Vovsha et al., 2003; 2004b; Bhat and Pendyala, 2005; Bradley and Vovsha, 2005; Gliebe and Koppelman, 2005).

In contrast to the existing literature which has tended to focus on weekday behaviour, this study has developed a weekend mode choice model with joint household travel, revealing various differences in travel behaviour between weekdays and weekends. This is the second area in which a contribution has been made. New findings include the difference in proportion of joint household travel, shared activities, and VOTs between weekend and weekday travel. In the absence of good estimates for weekend VOTs, for example, 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). However, it was found that VOTs are higher on weekends than
on weekdays, adding to international evidence of higher weekend VOTs (Ramjerdi et al., 1997; Kato et al., 2010; WebTAG, 2011a) and supporting the argument that people place a higher value on time spent on joint household activities (Fujii et al., 1999; Prasetyo et al., 2003). This study has also shown that these differences require different transport management measures aimed to alleviate traffic congestion and encourage public transport use on weekdays and weekends.

In evaluating the impact of joint household travel on public transport strategies and travel demand forecasting, a parallel analysis was undertaken to allow for comparisons between the individual and the joint household travel analysis over many scenarios. The findings were reached through inspection and comparison of simulation outcomes. It was found that the modal shift from the car to the PT mode in a model with joint household travel gives different responses to those of a model without joint travel. The better behavioural underpinning of a modelling approach which includes joint travel suggests the effect on mode choice of improved PT services and changes to employer-based policies accrues to individual travel only. This sends a strong message to policy makers and transport practitioners on the dangers of not taking account of joint household travel in policy analysis and travel demand forecasting. Whether modelling without joint travel overestimates or underestimates the modal shift response depends on the way the effect of a spuriously larger affected market offsets the reduced sensitivity of the model to the change as discussed in Section 6.6.

**7.4 Limitations and Future Research**

This thesis has developed a typology of tours and empirical models which add to the literature in several aspects; however, these also come with certain limitations, many of which are considered necessary in the estimation of the empirical models and the usefulness of the results. The limitations are discussed below to highlight the scope of the contributions and to identify areas for further research.

In terms of tour typology, the empirical analysis has combined joint outbound half-tour with the drop-off pattern (J2) and joint inbound half-tour with the pick-up pattern (J3). Decomposing these joint tour patterns into separate categories was constrained by low observation of these separate tour patterns in the empirical data. This limitation also means that kiss and ride tours are not distinguished from drop-off tours which has not allowed additional insights into the differences in multimodal behaviour between the passenger and the driver for this joint travel arrangement. In the current model, this difference can only be
inferred by combining the choices of joint tour pattern and tour main mode. For example, if the main mode of a drop-off tour is PT, then the person taking this tour type is most likely to be a passenger undertaking a multimodal journey with the car being the access mode, but if the main mode is the car, the person having a drop-off tour is a car driver with single mode. Nevertheless, joint access to a train station by walking without joint onward travel by PT is also considered as a drop-off tour, albeit this tour is less common. Thus, more insights would be gained if the model could consider PT tours with K&R and P&R as separate modes, requires more observations and could be overcome by pooling more waves of the Sydney HTS data to give more observations of infrequently observed choices for parameter estimation. However, this has a downside of muddling time-series and cross-section information.

Another constraint related to the dataset is its limited access to the real X, Y coordinates of the households, schools and workplaces due to confidentiality issues. This means that some aspects of the land use patterns, such as the street connectivity and ease of walking, have to be analysed at the TZ level with a loss of variation in land use characteristics across households within the same TZ. To minimise this loss of variation, this study has used a buffer area around the TZ centroid and has compared this with the TZ boundary to choose a better aggregation method. However, it would be ideal to use the real X, Y coordinates as the centres of the buffers.

A common limitation to this thesis and other studies of intra-household interactions is the use of an ‘old-fashioned’ survey which does not (fully) ask questions about the travel party size and travel party composition. Although the procedure developed in Chapter 4 for processing the data has shown a high level of accuracy and has overcome this shortcoming, the technical effort required would be reduced substantially if quality data were available. This highlights the need for improvements in survey activity such as computer-automated logical checks of the consistency of responses amongst different household members or GPS-assisted surveys. These improvements, rather than the post processing of data, will help to solve the deficiencies of existing travel surveys in a more principal way.

With respect to the effect of land use patterns on travel behaviour, an important limitation to this study is the phenomenon known as residential self-selection as reviewed in Section 2.1.2. Whilst the results of this study found some strong correlations between various aspects of land use patterns and travel behaviour, it is hard to know how much the effect is attributed to
the land use itself as opposed to individual’s preferences or attitudes. It is possible that
travellers who prefer to use PT choose to reside in areas with a good PT service, and thus use
PT more than those with a weaker attitudinal pre-disposition (Handy et al., 2005; Mokhtarian
and Cao, 2008; Cao et al., 2009). The cross-sectional design and the lack of attitudinal
information of the Sydney HTS data used in this study means it is not possible to isolate the
effect of land use patterns from individual/household preferences on travel behaviour.
Another limitation related to the effect of land use patterns on travel is that there are many
other variables that could have been used to describe land use characteristics. Due to
correlation and multicollinearity issues, all land use characteristics relevant to the determinant
of joint travel arrangements and their mode choices could not be included in the empirical
models. As a result, it is not possible to separate the effect of various land use aspects from
each other (e.g., rail density vs. mixed opportunity density). Although this study has explored
a broad set of land use characteristics and specification, finding suitable land use measures
and their appropriate specification to explain travel behaviour remains a challenge and would
require further research (Lochl and Axhausen, 2010).

With regard to the discrete choice modelling approach used in this study, improvements may
be achieved in many directions. One potential enhancement is to take account of 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. A latent class
(LC) panel modelling approach would be able to capture this state dependence effect as well
as individual’s heterogeneous preferences. This would require the data to be structured in
such a way that describes the sequence of home-based tours making up an individual daily
activity-travel pattern where each tour is characterised by two dimensions of joint tour type
and tour main mode as done in this thesis. Distinct classes of individual/household
preferences for joint household activities and travel would then be specified using variables
describing individual responsibilities, household context, social and spatial constraints, and
choice situation. This LC panel approach would allow joint household travel, individual
heterogeneous preferences and the dependence of observed choices to be modelled explicitly.
However, the model structure would become complex very quickly as the number of specified
latent classes increases. For a model with three latent classes, for example, each observation
in this model will face with a choice set comprising of 90 alternatives (3 main travel modes
times 10 joint tour types times 3 classes = 90). This raises difficulties with the model
estimation and application. To overcome this difficulty, a practical model has to make a trade-off between understanding joint household travel and the state dependence of individual choices. An example of such the trade-off would be reclassifying the nine joint tour patterns into a fewer number of groups such as individual tour, partially joint, fully joint and mixed tours. For the interest of this study, intra-household interactions in individual choice take priority over the state dependence.

Another potential area for further research relates to the way in which escorting tours are processed in practice. As shown in Section 5.2.3, shared activities chained into joint tours, for households with more than one student attending the same school, they are very likely to drop-off and 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 (Vovsha and Petersen, 2005). A further refinement on modelling escorting behaviour would be to consider explicitly multiple drop-off and pick-up bundles, especially for school travel, with multiple household students being dropped off or picked up at different places using the same car tour. However, these improvements to modelling would be possible only with a better data quality.

More generally, the current modelling technique treats the individual as the decision-making unit and uses a typology of joint household tours as the 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) or the generalised PCCL described in Section 3.4.3, may add more insights into joint household travel arrangements. The application of the PLCC modelling approach to the current issues of joint travel and mode choice resulted in a model structure that was so complex that the estimation would not converge. This requires further methodological developments to capture complex interdependent decisions of multiple-person households or a better procedure for the estimation of the generalised PCCL model.

Another avenue for future research is to incorporate the mode choice model with joint household travel developed in this thesis into an activity-based modelling framework to improve practically the performance of regional travel demand models. A possible way could be to place this model after individual DAPs have been generated and the main destination and time of day models have been applied. In this way, outcomes from the DAP, main
destination and time of day models can be used in the model of individual choice of joint travel patterns. This model would classify tours into different type using the joint tour typology, and the mode choice model would then be applied, conditioned on the individual choice of joint tour patterns. Further on, other models that form the rest of the activity-based framework (intermediate stop frequency, location, departure and arrival times, and trip mode models) could be applied to each tour, and the network assignments and skim matrices can then be performed. Outcomes from the lower models including the travel times and travel costs would then be fed back to the tour-based mode choice model in an iterative manner until convergence in all levels is obtained.

Finally, the focus on joint tour patterns and tour main modes as the elemental alternatives of the modelling system represents the various ways in which household members chain joint household activities and travel into a home-based tour and choose the main mode to access out-of-home activities. Thus, the current model deals with choices at the tour level to understand the influence of joint household travel on travel mode choice, given that a tour has been undertaken. This has important implications for travel demand management and policy formulation as discussed in Section 7.2 above. The value of this approach also lies in its capability of analysing transport policies such as those relating to HOV/HOT lanes and special public transport ticket prices for group travel as demonstrated in the policy analysis (Section 6.5). An alternative approach to give such insights would be to develop a tour typology to characterise daily activity travel patterns and model tour generation and tour structure simultaneously at an upper level of the activity-based modelling framework. The mode choice would then be conditional on the tour structure. This would require a further segmentation of alternatives which would have resulted in fewer observations, and thus, a loss of precision in estimating the effect of economic and situational variables on the propensities to pursue infrequently observed joint household travel arrangements, which are important to the research focus.
REFERENCES


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


APPENDICES

Appendix 1 Comparison of weekday and weekend joint tour patterns by

(a) Household size

(b) Household lifecycle

* Older children (aged over 15 years) may be present in the households
(c) Individual age

Data source: Sydney HTS 2007 - 2010.
Appendix 2 Observed frequency of daily activity-travel patterns by household choice of joint travel patterns, average weekday in Sydney 2007 – 2010

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Total DAPs: 4,228, 1,743, 603, 351, 411, 318, 1,341, 165, 345, 605, 29

*An individual DAP is a sequence of home-based tours undertaken on a day. Each tour is characterised by joint tour type (J1 – J9) and travel mode (PT, Car, Walking). For example, a household member with a DAP of the type “J9Car-J1Car” makes 2 tours by car, the first tour is individual (J9) and the second tour is fully joint (J1).

†Empty cells indicate no observed combinations in the empirical data.