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REDUCING RELIANCE ON PRIVATE VEHICLES: A SUSTAINABILITY IMPACT ANALYSIS OF CAR SHARING AND RIDE SHARING

Niamh Rabbitt

A dissertation submitted to the University of Dublin in the partial fulfilment of the requirements for the degree Doctor of Philosophy

November 2014

Department of Civil, Structural and Environmental Engineering

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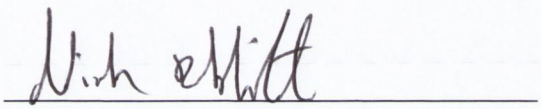

Niamh Rabbitt

SUMMARY

At the broadest level, the objective of this research work was to examine approaches to improving the sustainability of transport. This objective is accomplished by evaluating the impact of introducing two methods of reducing reliance on private cars to a population. The two methods evaluated are 1) Car Sharing and 2) Ride Sharing. Throughout this thesis these are defined as follows:

Car Sharing: the model of car rental where members rent cars from convenient points on a short term basis i.e. minimum rental periods are typically half an hour.

Ride Sharing: Two or more individuals, who are at best tenuously acquainted, using modern technology to arrange to share a common journey in a car which belongs to one of the individuals.

When carrying out the impact evaluation, the three pillars of sustainability: environmental, economic and social; are used as a framework within which to evaluate the impact, and the population of County Dublin, Ireland is used as a sample population.

In summary, the four main aims of this thesis are:

1) To conduct a detailed literature review in the following areas:
    a. Car Sharing,
    b. Ride Sharing,
    c. The link between social sustainability and transport
2) To achieve a better understanding of the relationship between an individual's travel pattern and a) their spending on domestic travel, b) the environmental impact of their domestic travel and c) their wellbeing.
3) To investigate the potential of car sharing in Dublin to reduce reliance on private vehicles while improving economic and environmental aspects of transport.
4) To investigate potential of ride sharing in Dublin to reduce reliance on private vehicles while improving economic and environmental aspects of transport.

The first chapter introduces the broad context and concepts which form the basis of the thesis. The research to date relating to car sharing, ride sharing and travel and wellbeing is then discussed in detail in Chapter 2. Chapter 3 describes the datasets used, including the development and distribution of a comprehensive travel survey which was administered to 2,639 individuals around Ireland.

In Chapter 4 responses to this survey are analysed and a cost of travel and carbon dioxide emissions of travel calculated for each respondent. Survey data on the link between private vehicle ownership and usage and individual wellbeing is also analysed. The results of this research show a very strong link between an individual's spending on transport and car ownership, an individual's carbon dioxide emissions of transport and their level of car travel and no link between an individual's car usage or ownership and wellbeing.

Chapter 5 presents the research work on car sharing. This work contributes to the research on car sharing by developing a methodology with which to evaluate the feasibility and impact of a car sharing service operating in a given geographic area. The chapter first describes the three stage methodology developed to evaluate the environmental and economic impacts of car sharing. It subsequently presents the results of this methodology when applied to the population of Dublin and the population of Ireland. The results of the analysis are presented as a geographic analysis of population uptake, an economic and environmental analysis of individual changes to costs and carbon dioxide emissions of travel, and a combined analysis which uses a scenario based approach to calculate the environmental and economic impacts of the rollout of a car sharing service in both the Dublin area and across Ireland.

Chapter 6 and Chapter 7 present the research work on ride sharing. This work contributes to research on ride sharing through the development and subsequent analysis of models of a ride sharing service. Using open source software Chapter 6 builds a model in four stages. The model is used to analyse how user behaviour affects the number of matches a ride sharing service might achieve. A sample of morning commute journeys from the POWSCAR dataset (CSO, 2012e) is used as a population participating in ride sharing. Based on the results of Chapter 6, Chapter 7 then calculates the environmental and economic impacts which would occur should a ride sharing service successfully operate in Dublin. Together the results of Chapter 6 and Chapter 7 add considerably to the understanding of how and where a ride sharing service might successfully operate. In particular the results suggest the importance of registering individuals who are willing to adopt a passenger or a driver role as needed and the importance of repeat registration by those who successfully identify matches.

The final chapter, Chapter 8 concludes the thesis with a summary of the key findings of the research and the contribution to knowledge. This chapter also discusses the shortcomings of the research and identifies the topics which require further investigation.

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LIST OF ABBREVIATIONS

AT Active Traveller

BCMA Base Case Matching Algorithm

CC Condition Component

CO_2 Carbon Dioxide

CS Car Sharing

CT Car Traveller

CSM Car Sharing Member

CSO Central Statistics Office

CSS Car Sharing Service

DART Dublin Area Rapid Transit

DC Depreciation Code

DLTC Dun Laoghaire Town Centre

DMA Dynamic Matching Algorithm

EPSSU Energy Policy Statistical Support Unit

FMA Flexible Matching Algorithm

GPS Global Positioning System

HOV High Occupancy Vehicle

IPCC Intergovernmental Panel on Climate Change

LU Likely Users

LUCO Low Usage Car Owners

momo An EU funded research program - More Options for Energy Efficient Mobility through Car-Sharing

MoP Month of Purchase

NCT National Car Test

NRMA National Roads and Motorists Association, Australia

NTS National Travel Survey (Central Statistics Office, 2011b)

OMSP Open Market Selling Price

POWSCAR Place of Work, School or College – Census of Anonymised Records

ppm Parts per million

PT Public Transport Traveller

RC Radical Change

RS Ride Sharing

RSS Ride Sharing Service

SAPS Small Area Population Statistics

SIMI The Society of the Irish Motor Industry

SMA Social Matching Algorithm

VRT Vehicle Registration Tax

LIST OF SYMBOLS

$\overline{\overline{X}}$ A double bar above a symbol indicates that the parameter described has been scaled.

AT_n Time in minutes after midnight at which an individual (n) arrives at their work location.

B A group (batch) of registrants who register with the service at a point after matching has commenced.

B_f an individual (f) who registers within a batch of registrants and is flexible to be either a driver or a passenger. These are similar to P_f.

B_i an individual (i) who registers within a batch of registrants seeking to travel as a passenger. These are similar to P_i.

B_j an individual (j) who registers within a batch of registrants seeking to travel as a driver. These drivers are similar to D_j, however they are not registered from the start of the matching process but instead register at a point after matching has commenced.

BL Booking Length, the amount of time for which a CS vehicle is booked.

CC Condition Component.

CP Chance Parameter.

D The set of all individuals who register with the matching service, are willing to act as drivers and are not yet matched as passengers.

DC Depreciation Component.

$Dist_H$ A constraint within the model which sets a maximum distance (km) between a passenger's home (X_{Hi}, Y_{Hi}) and a driver's home (X_{Hj}, Y_{Hj}), above this maximum distance the match is excluded.

$Dist_n$ Distance between an individual's (n) home location and work location

$Dist_T$ A constraint within the model which sets a maximum distance for the sum of (a) the distance between a passenger's home (X_{Hi}, Y_{Hi}) and a driver's home (X_{Hj}, Y_{Hj}) and (b) the distance between a passenger's work (X_{Wi}, Y_{Wi}) and a driver's work (X_{Wj}, Y_{Wj}). Above this maximum distance, the match is excluded.

$Dist_W$ A constraint within the model which sets a maximum distance (km) between a passenger's work (X_{Wi}, Y_{Wi}) and a driver's work (X_{Wj}, Y_{Wj}), above this maximum distance the match is excluded.

D_j An individual driver (j) who regis.ters with the matching service offering lifts to passengers.

DT_n Time in minutes after midnight of an individual (n) departing a home location for their workplace.

f Subscript f is used to denote a parameter related to an individual who registers with the RSS as flexible to be either a driver or a passenger. These individuals are subsequently added to the passenger and driver pools and subscripts i and j are then used as appropriate.

$FYAG_n$ A number describing the five year age group of an individual (n).

G_n A number describing the gend.er of an individual (n).

HC Hire Cost.

HPY Hours per year, the number of hours per year a respondent is expected to rent the CS vehicle.

i Subscript i is used to denote a parameter related to an individual who is acting as a passenger within the model.

ID_j An individual driver (j) who registers with the matching service offering lifts to passengers, before any matches are made in the DMA (Model 4).

j Subscript j is used to denote a parameter related to an individual who is acting as a driver within the model.

K The average number of drivers assigned to each cluster when cluster centres are calculated.

K_i The cluster centroid whose scaled centroid is closest in Euclidean distance the scaled journey parameters of a passenger (i).

K_j The cluster centroid whose scaled centroid is closest in Euclidean distance the scaled journey parameters of a driver (j).

KMC_{CS} Cost per Kilometre travelled in CSS cars.

KMC_{PT} Cost per Kilometre travelled by Public Transport.

K_z An individual cluster.

m A sub-list of M containing only matches whose passengers have exactly 1 match.

m_1 The match in position 1 on the sub-list of matches (m).

M The set of all possible matches between drivers and passengers.

M_1 The match in position 1 on the list of all possible matches (M).

$M_{_j}$ The set of all possible matches for an individual driver (j).

MF Monthly Fee paid by a car sharing member to a car sharing service.

$M_{i_}$ The set of all possible matches for an individual passenger (i).

M_{ij} A matched journey between a passenger (P_i) and a driver (D_j).

MoP Month of Purchase Component.

n Subscript n is used to denote a parameter related to an individual within the Dublin commuter driver population.

NB The number of batches in which newly registering users are matched.

OMSP Open Market Selling Price.

P The set of all individuals who register with the matching service, are willing to act as passengers and are not yet matched as drivers.

PC_{dist} Annual distance in km travelled in private vehicles by a respondent.

PC_{time} Annual time in minutes spent in private vehicles by a respondent.

PC_{jour} Annual journeys made in private vehicles by a respondent.

P_j An individual passengers (i) who registers with the matching service seeking to travel as a passenger.

R The full of list (record) of assigned matches.

R_{ij} An assigned match between an individual passenger (i) and an individual driver (j)

RR Retention Rate, the proportion of unmatched passengers at the end of batch matching who are retained and added as passengers to the next batch of passengers.

S A constraint within the model which sets a maximum number of available seats in each driver's car at the start of the matching process.

SEG_n A number describing the socio-economic group of an individual (n)

SD_{ij} The "social difference" between a driver (j) an a passenger (i)

S_j The number of (remaining) seats available to passengers in the car of an individual driver (j)

t A constraint within the ride sharing models which sets a maximum difference (minutes) between a passenger's desired arrival time (AT_i) and a driver's desired arrival time (AT_j)

T_1 Is the number of journeys made by a respondent using the mode(s) specific to the travel category on which the respondent made the greatest number of journeys.

T_2 Is the number of journeys made by a respondent using the mode(s) specific to the travel category on which the respondent made the second greatest number of journeys.

TS Is the travel category to which an individual respondent is assigned.

TS_D Is the travel category on which a respondent travelled the greatest distance.

TS_T Is the travel category on which a respondent made the greatest number of journeys.

TTCJ Average Travel Time per Car Journey.

X_{Hn} X co-ordinate in metres of an individual's (n) Home location.

X_{Wn} X co-ordinate in metres of an individual's (n) Work location.

Y_{Hn} Y co-ordinate in metres of an individual's (n) Home location.

Y_{Wn} Y co-ordinate in metres of an individual's (n) Work location.

z Subscript z is used to denote a parameter related to an individual cluster within the model.

α A set of user proportions used to calculate membership numbers, cost savings and emissions rates when estimating the overall economic and environmental impact of car sharing.

δ_{opp} Opportunity Costs associated with Car Ownership.

δ_{dep} Depreciation Costs Associated with Car Ownership.

δ_{ann} Annual Costs Associated with Car Travel.

δ_{ann} Fortnightly Costs Associated with Car Travel.

β_{ann} Annual Costs Associated with travel on Public Transport.

β_{exp} Fortnightly Costs associated with travel on Public transport.

M_{α} Is the total number of members of the CSS when the α set of user proportions is used.

θ_{oth} Fortnightly Costs associated with travel in Taxi's and CSS vehicles.

ρ_{ACT} The proportion of non-private vehicle distance travelled by the respondent on foot and by bicycle.

ρ_{Bus} The proportion of non-private vehicle distance travelled by the respondent on the Bus.

$\rho_{LU.\alpha}$ The proportion of members of the CSS who are categorised as LU when the α set of user proportions is used.

$\rho_{LUCO.\alpha}$ the proportion of members of the CSS who are categorised as LUCO when the α set of user proportions is used.

ρ_{PT} the proportion of non-private vehicle distance travelled by the respondent on Public Transport.

$\rho_{RC.\alpha}$ the proportion of members of the CSS who are categorised as RC when the α set of user proportions is used.

ρ_{Train} the proportion of non-private vehicle distance travelled by the respondent on the Train.

ϕ A unit area in which car sharing takes place.

X_1 Adult residents of 1-2 person households.

$\mathbf{X_2}$ Age between 25 - 49 years.

$\mathbf{X_3}$ Working or self-employed.

$\mathbf{X_4}$ Education qualification includes at least an ordinary degree.

$\mathbf{X_5}$ Adult residents of no car households.

$\mathbf{X_6}$ Adults who travel to work using modes other than driving.

$\mathbf{X_7}$ The number of adults in a unit area.

$\mathbf{X_\phi}$ The minimum value of $X_{1\phi} \ldots X_{6\phi}$ for unit area ϕ.

$\mathbf{X_{avg\phi}}$ The mean value of $X_{1\phi} \ldots X_{6\phi}$ for unit area ϕ.

Ψ_1 A unit area which meets the conditions for early rollout.

Ψ_2 A unit area which meets the conditions for middle rollout.

Ψ_3 A unit area which meets the conditions for late rollout.

Ψ_4 A unit area which has sufficient adult density to support a CSS but does not meet the conditions for late rollout.

Ψ_5 A unit area which does not have sufficient adult density to support a CSS

1 INTRODUCTION AND BACKGROUND

1.1 Introduction

Recent research and policy work on improving the sustainability of transport has focused on promoting a mode shift away from private vehicles towards modes with a lower environmental impact such as walking, cycling and public transport (e.g Akerman et al., 2000; United States Environmental Protection Agency, 2011; Green, & Plotkin, 2011). It is believed that these modes of transport have the potential to meet a greater proportion of travel needs than is currently the case (Redman, Friman, Gärling, & Hartig, 2013). However historical evidence demonstrates that achieving a modal shift is difficult and these alternative modes may not provide a solution which meets all of an individual's transport needs (Bannister & Marshall, 2000).

There is therefore also interest in enabling private vehicles to be used more efficiently, both through improved technology and through behavioural change. This work addresses a significant gap in research by evaluating the sustainability impacts of introducing services which enable private vehicles to be used more efficiently to a population. Such services provide access to private vehicle travel without the capital costs which attend private vehicle ownership. Thus they facilitate a mode shift to other forms of transport while maintaining an individual's ability to engage with economic and social activities which require private vehicle access.

The potential impacts of introducing two methods of reducing reliance on private cars to a population are therefore evaluated. The two methods evaluated are 1) Car Sharing and 2) Ride Sharing. Throughout this thesis the following definition of each method[1] is used:

Car Sharing: the model of car rental where members rent cars from convenient points on a short term basis i.e. minimum rental periods are typically half an hour.

Ride Sharing: Two or more individuals, who are at best tenuously acquainted, using modern technology to arrange to share a common journey in a car which belongs to one of the individuals.

When carrying out the impact evaluation, two of the pillars of sustainability: environmental, and economic; are used as a framework within which to evaluate the impacts, and the population of County Dublin, Ireland is used as a sample population.

[1] The literature on which these definitions are based in discussed in more detail in Chapter 2.

This chapter introduces the context and concepts which form the basis of the thesis. Section 1.2 provides a broad context for the work, highlighting the importance of transport as a contributor to carbon dioxide (CO_2) emissions. The following sections introduce the concepts of sustainability, sustainable development and sustainable systems. The subsequent two sections then develop the concept of sustainability as it relates to this research work, namely by describing approaches to the measurement of sustainability and by discussing the relationship between sustainability and transport. The final two sections delineate the research objectives and the overall structure of this thesis.

1.2 Irish Context

Under the EU Climate Energy Package, Ireland has agreed to reduce greenhouse gas emissions to 20% below 2005 levels by the year 2020 (, Pallemaerts, & Kelly, 2010). Irish government statistics (Energy Policy Statistical Support Unit [EPSSU], 2012) illustrate that transport is by far the largest CO_2 emitting sector in Ireland, accounting for 33% of all CO_2 emissions in 2012. This amounts to 12,399kt of CO_2, which is 1.5 times the energy-related CO_2 emissions of industry. In Ireland, 97.9% of the energy used for transport is from oil derived fuels. There has also been very limited decoupling of CO_2 emissions from transport energy consumption since 1990. In the time period 1990-2012 transport CO_2 emissions experienced an average growth rate of 3.3% Vs less than 0.5% across the other four sectors. For these reasons, methods of reducing the CO_2 emissions of transport are a major area of policy and research focus.

In common with many countries worldwide, the greatest contributor (45%) to transport CO_2 emissions in Ireland is travel in private vehicles (EPSSU, 2012). However, private vehicles offer a number of advantages both economically and socially. Private vehicles allow on demand travel to any desired destination. An individual with access to a private vehicle therefore has superior access to workplaces, shopping facilities and other important spheres of economic activity. Similarly, ownership of a private vehicle enables participation in leisure pursuits, social engagements, access to healthcare etc. (Raphael, Stoll, Small, & Winston, 2001). Care must therefore be taken that efforts to reduce travel in private vehicles are implemented in a sustainable manner, i.e. that limiting and mitigating the environmental impacts of private cars does not adversely affect economic and social development.

1.3 Sustainability and Sustainable Development

Before evaluating sustainable transport, in particular the sustainability impacts of introducing car and ride sharing services, it is important to understand exactly what is meant by sustainability and sustainable development, and to place these concepts in the context of the transport services being evaluated. This section therefore reviews the literature on sustainability and sustainable development and describes the development of the concepts.

The concepts of sustainability and sustainable development have been of great interest for some 25 years. Taking Sustainable Development first, though much debate has taken place, little consensus has been reached on a precise meaning for the phrase. The term was defined in 1987 by Gro Harlem Bruntland as

> *"Development which meets the needs of the present without compromising the ability of future generations to meet their own needs."*
>
> (Bruntland, 1987, p.41)

Sustainability is the capacity to endure (Gershenson, 2013). A positive change in the level of sustainability can be regarded as one which reduces the risk of compromising the ability of future generations to meet their own needs, i.e. a change which increases the capacity to endure. Since 1987 the debate and literature have moved forward, both along the theme of sustainable development and along the theme of sustainability.

Bruntland's definition continues to be a central focus of the wider discussion attempting to more precisely define and interpret the concepts of sustainable development and develop indicators with which to measure it. Parris and Kates (2003) reviewed publications characterising sustainable development. Their results were framed in terms of what specific contributors to the debate identified as being worthy of sustaining and worthy of developing. They found that groups and institutions tend to acknowledge the many multiple and conflicting objectives to be both sustained and developed but then adopt implicit objective functions that take the forms of such statements as sustain only, develop mostly, develop only but sustain somewhat, sustain, or develop—for favoured objectives. As can be seen in Table 1.1, when all twelve of the publications reviewed were considered as a whole, close agreement can be found with those objectives originally stated by Bruntland (1987).

Table 1.1: Taxonomy of sustainable development goals (Parris & Kates, 2003)

What is to be Sustained	What is to be Developed
Nature Earth Biodiversity Ecosystems	**People** Child survival Life expectancy Education Equity Equal Opportunity
Life Support Ecosystem services Resources Environment	**Economy** Wealth Productive Sectors Consumption
Community Cultures Groups Places	**Society** Institutions Social Capital States Regions

Costanza and Patten (1995) also reviewed the debate and found that most definitions of sustainable development contain elements of 1) a sustainable scale of the economy relative to its ecological life support system; 2) an equitable distribution of resources and opportunities between present and future generations; and 3) an efficient allocation of resources that adequately accounts for natural a capital.

There are however difficulties with Bruntland's definition. As Marshall and Toffel (2005) conclude, to avoid impeding the ability of future generations to meet their own needs requires predicting both their needs and their abilities, an impossible task. However no other piece of work has emerged as a replacement and as the Bruntland definition (1987) continues to predominate, it is adopted here.

1.3.1 Sustainable Systems: Collaborative Consumption

Efforts to improve sustainability take place within a system. In the case of this research, both of the services under evaluation improve sustainability by introducing a change to a business system. The car sharing service evaluated in this thesis uses new technologies (online payment, global positioning system [GPS] tracking, reputation systems, smart phones) to facilitate short term vehicle rental by customers. Similarly the ride sharing service evaluated in this thesis uses these new technologies to enable individuals to share journeys. Both services facilitate access to private vehicle travel without the attendant capital costs, i.e. they move from a business model with a

value proposition based on ownership to a business model based on offering access (Onetti, Zucchella, Jones, & McDougall-Covin, 2012).

This access business model, often called "Collaborative Consumption" is an emerging area of interest in the field of sustainable systems. Collaborative consumption is a term that describes the new systems of swapping, bartering, trading and renting which are based on new technology (Botsman & Rogers, 2010). These systems allow existing resources (e.g. cars) to be used more intensively, thus potentially reducing the environmental impact of human activity. There is therefore increasing interest in the collaborative consumption business model as a means to promote sustainability (e.g. Economist, 2010; Walsh, 2011) however little recent academic work has been done on the concept as currently defined.

Collaborative consumption redefines the typical roles taken by business and the typical life cycle of products. Figure 1.1 is provided to summarise a typical product life cycle under the more typical ownership model. A business sells a good to a customer who then uses of it and at some point in the future disposes of it usually through landfill or recycling.

Figure 1.1: Typical Product Lifecycle

Collaborative consumption businesses facilitate the extension of a products life cycle by using new technologies to enable customers to resell the product or share their usage of a product with others (Botsman & Rogers, 2010). By enabling the more intensive use of existing resources, it is argued that collaborative consumption business models are more sustainable than standard business models (Phipps et al., 2013)

While some businesses engaged in these areas historically, the advent of new technology, specifically mobile phones, the internet and in particular smart phones, enables these redistribution type businesses to operate on a scale not possible in the past.

Two authors have made significant recent contributions in the non-academic literature. These are Rachel Botsman and Roo Rodgers "What's mine is yours: The rise of Collaborative Consumption" (2010) and Lisa Gansky "The Mesh" (2010). Botsman and Rogers work is focused on the context, present status and future of collaborative consumption. Botsman and Rogers (2010, pp.75-93) propose four principles of collaborative consumption shown in Table 1.2. Gansky's work focuses on the business processes and technical aspects of what she calls "The Mesh". Gansky (2010, p.16) also proposes four principles of mesh business which are summarised in Table 1.3 below.

Table 1.2: Principles of Collaborative Consumption (Botsman & Rogers, 2010, pp.75-93)

Principle	Meaning
Critical mass	Sufficient momentum in the system to make it self sustaining, availability of choice
Idling Capacity	The time products owned are not being used, or not being used to their full capacity
Belief in the commons	Desire of community members to add value to the community
Trust between strangers	Desire to self organise and build reputation

Table 1.3: Characteristics of Collaborative Consumption (Gansky, 2010, p.16)

Characteristic	Meaning
Sharing	The core offering is something that can be shared within a community, market or value chain, including products, services and raw materials.
Advanced Web and Mobile Data Networks	These are used to track goods and aggregate usage, customer and product information.
Physical Goods	The focus is on shareable physical goods, including the materials used which makes local delivery of services and products – and their recovery – valuable and relevant
Social Network Services	Offers, news, and recommendations are transmitted largely through word of mouth, augmented by social network services

There is a clear emphasis with both authors on the power of collaborative consumption to connect people and also on the need for sufficient people to engage with the businesses and concepts involved. Both Botsman and Rogers, and Gansky propose similar core principles of design for collaborative businesses and products. These are listed in Table 1.4 below.

Table 1.4: Design for Collaborative Business (Botsman & Rogers, 2010,pp. 188-198; Gansky, 2010, p.53)

Botsman & Rogers	Gansky
Putting Systems First	Flexible
One for Life	Durable
Cradle to Cradle	Sustainable
Ability to maintain, repair and upgrade	Reparable

Historically, economic and social developments have resulted in environmental degradation (Acaravci & Ozturk, 2010). Conversely, improvements in environmental behaviour often have a negative economic impact.

In the traditional business cycle outlined in Figure 1.1, companies profit by selling new goods to individuals who wish to replace redundant goods, or by selling inputs for products to other companies. Typically when individuals or companies choose to become more environmentally conscious, products which have reduced inputs and/or a longer life cycle are promoted. This can have a negative economic impact as companies sell fewer goods overall, in short a positive environmental measure has a negative economic impact.

Companies which use the collaborative consumption model profit from longer product life-cycles and more intensive use of individual products (Botsman & Rogers, 2010). For instance, under the typical business model an individual might purchase a power tool for a specific task, using it briefly then storing it indefinitely. This behaviour has a positive economic impact but a negative environmental impact. An environmentally conscious individual might borrow the tool from an individual who has already purchased it or simply not perform the task if no tool is available. As no money changes hands, no economic benefit will be created. A company operating with a collaborative consumption model, allows environmentally conscious individuals to extend their network to strangers who may have the tool which they need. The company then facilitates the tools rental at a small charge, making a profit for itself and the renter, while enabling any individual to complete their task without the purchase of expensive tools.

Thus companies operating in the collaborative consumption space may mitigate the potential negative economic impact of environmentally conscious behaviour, increasing the overall sustainability of the system.

1.4 Measuring the Sustainability of a System

The process of achieving a meaningful, workable way of measuring sustainability has also been approached by a variety of researchers. Two ways of expressing and measuring the idea of sustainability in the literature were identified by Genaidy et al. (2010). These were approaching sustainability as or (1) a goal or limit which can be achieved by following a system and/or obeying a defined set of rules, (2) a set of behaviours and properties of systems.

1.4.1 Objectivist Approach

The first group of approaches are described as *objectivist approaches* by Schaefer and Crane (2005) because they try to determine objectively maximum sustainable consumption levels and actions that need to be taken to stay within these levels. Several authors have proposed rules and methods of setting limits which follow the objectivist approach. For instance Daly (1990) proposed two principles of sustainable development. First that harvest rates should equal regeneration rates (sustained yield). Second that waste emission rates should equal the natural assimilative capacities of the ecosystems into which the wastes are emitted. Regenerative and assimilative capacities must be treated as natural capital, and failure to maintain these capacities must be treated as capital consumption, and therefore not sustainable

These principles were further refined by Robèrt et al. (2002), in their proposed system "The Natural Step" which consists of four ultimate sustainability objectives:

1. Eliminate our contribution to systematic increases in concentrations of substances from the Earth's crust
2. Eliminate our contribution to systematic increases in concentrations of substances produced by society
3. Eliminate our contribution the systematic physical degradation of nature through over-harvesting, introductions and other forms of modification.
4. Contribute as much as we can to the meeting of human needs in our society and worldwide, over and above all the substitution and dematerialization measures taken in meeting the first three objectives.

While the objective approach provides limits for sustainable systems, no satisfactory work has emerged describing how systems can be restrained within these limits or how we can measure our progress in doing so.

1.4.2 Behavioural Approach

The second approach, that of treating sustainability as a set of behaviours, focuses on a core idea which emerged early in the debate on sustainability (e.g. Daly, 1990; Pearce, 1988) that of the three pillars of sustainability. These three pillars, also termed capital stocks - Economic, Social and Environmental - have remained a constant theme throughout the debate. The inter relationship between these three or more competing areas of interest is typically shown in venn diagram format and differing arrangements have been proposed (see Moffatt, 2008). The most common arrangement is three simple overlapping circles and is shown in Figure 1.2.

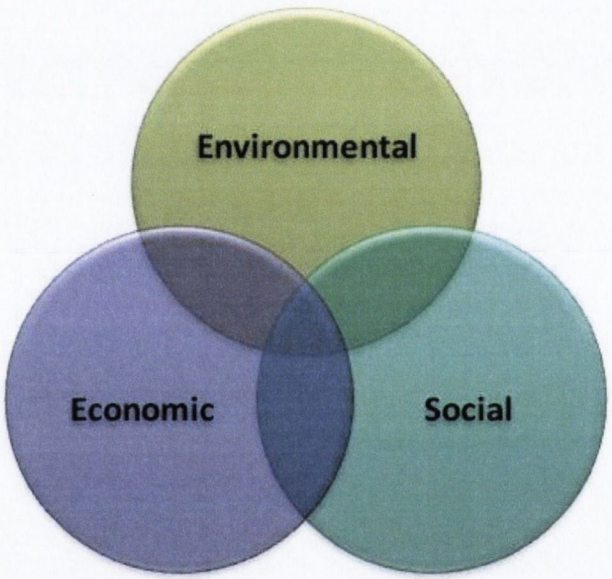

Figure 1.2: Three Pillars of Sustainability

In the three pillars approach progress is made towards sustainability when a change to a system produces improvements in economic, environmental and social indicators. Another facet of the discussion on the three pillars of sustainability is the debate on what is termed weak vs. strong sustainability (Ayres, van den Berrgh ,& Gowdy, 2001)

While still using the three pillars of environmental, social and economic as the core principles, the debate about strong vs. weak sustainability centres on whether each of these capitals is interchangeable. For proponents of "weak" sustainability, degradation to an environmental stock (e.g. an eco-system) may be compensated for by an improvement to other stocks, e.g. an economic development. Environmental benefits can therefore be measured in economic terms

and a balance struck. An improvement in sustainability can occur even when a positive environmental change has a negative economic impact.

For proponents of "strong" sustainability, each stock is independent, and not inter-changeable. Economic and social systems must remain within the limits of ecological systems and it is not possible to express environmental degradation in monetary units (Moffatt, 2008). An improvement in sustainability cannot occur unless the change produces improvements in the economic, social and environmental indicators.

For proponents of the "pillars" approach to sustainability, sustainability is measured by individually measuring environmental, economic and social qualities of the system being examined. Improvements either in the individual (strong sustainability) or aggregate (weak sustainability) measures are considered to indicate a move towards a more sustainable system, i.e. sustainable development. While the system becomes more sustainable, it is never considered "sustainable". In contrast to the objectivist approach, sustainability is not regarded as a goal to be achieved.

1.4.3 Approach in this research

The pillars approaches and the framework approaches are not mutually inconsistent as they focus on different aspects of the problem posed by attempts to define sustainability. Referring back to the earlier discussion of sustainable development in section 1.3, the pillars approaches can be considered as describing what is to be sustained while the framework approaches describe how it is to be sustained. For illustration, one can consider how each approach would consider an indicator such as the ecological footprint. The objectivist approach will try to establish the maximum allowable ecological footprint per capita, and devise a set of rules to ensure that limit is not reached. Below that limit, the objectivist will consider the system to be sustainable. The behavioural approach will try to establish the current value of the ecological footprint and to reduce it (i.e. reduce the associated environmental degradation), while also monitoring the impacts of those reductions on economic and social development. For the behavioural approach, the system will become more sustainable but will never "be sustainable".

In terms of this research, both approaches are of interest, however while the objectivist approach provides guidelines, rules and an end goal, there is little or no agreement on how to appropriately set goals, how an evaluation can be made that a system meets these goals or of how close a system is to the ability to meet these goals. In contrast, though less specific in many regards, the

three pillars approach provides a useful guide to evaluating improvements in sustainability, i.e. measurement of environmental, economic and social impacts at specific points in time. For this reason, the three pillars concept forms the basis of this thesis.

1.5 Sustainability and Transport

At both a macro and micro scale, travel and transport is an interesting issue for sustainable development. Transport both supports international industry and is itself a major international industry (Banister & Berechman, 2001; Page, 2005). It facilitates economic activity and growth. Good transport also facilitates individual engagement with important aspects of the social realm such as: healthcare, community activities, holidays, leisure activities, education and perhaps most importantly work. However, transport may also have negative impacts on development both at the macro and micro scale. From an environmental point of view, transport contributes to both resource degradation and pollution. From an individual point of view, inadequate transport may impact on personal quality of life, causing difficulty accessing work or healthcare, inefficient use of time and discomfort. This section provides a brief introduction to the issues linking transport and sustainability with a particular focus on private vehicles.

1.5.1 Environmental Sustainability

Growth in travel demand, vehicle use and vehicle ownership are intrinsically linked to adverse environmental impacts (Dargay & Gately, 1997,2007). Pollution resulting from CO_2 emissions and other gaseous emissions are the key concerns with respect to environmental sustainability and transport. Other issues such as resource exhaustion (i.e. the depletion of oil reserves), excessive noise and efficient use of land are also of interest.

Pollution is the presence in or introduction into the environment of a substance or thing that has harmful or poisonous effects. Pollution can affect all aspects of the natural environment, with air and water systems being particularly vulnerable. Pollution is also a key cause of system degradation. Bruntland discussed air pollution, especially that caused by CO_2 emissions from the burning of fossil fuels, as a key cause for concern:

> *"the burning of fossil fuels and the cutting and burning of forests release carbon dioxide (CO_2). The accumulation in the atmosphere of CO_2 and certain other gases traps solar radiation near the Earth's surface, causing global warming. This could cause sea level rises over the next 45 years large enough to inundate many low lying*

coastal cities and river deltas. It could also drastically upset national and international agricultural production and trade systems."

(Bruntland, 1987, p.12)

The pollutant, carbon dioxide, is the most important anthropogenic greenhouse gas. The most important recent document assessing the impact of increasing CO_2 emissions is the 2013 report of the Intergovernmental Panel on Climate Change (Stocker et al., 2013). The report summarises the key environmental problems which must be resolved to protect the interests of future generations. Three key threats to sustainable development can be identified in both the Bruntland (1987) report and the Intergovernmental Panel on Climate Change (IPCC) report (Stocker et al., 2013), namely system degradation, pollution and resource exhaustion. Of these, two – pollution and resource exhaustion, are of particular importance to the topic at hand.

In 2013, the IPCC concluded that global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 parts per million (ppm) to 391ppm in 2011. This concentration far exceeds by the natural range over the last 650,000 years (180 to 300ppm) as determined from ice cores. (Stocker et al., 2013). The burning of fossil fuels is a main contributor to rising atmospheric CO_2 levels. Pollution arising from the burning of oil by-products in transport is a major contributor to global warming.

1.5.2 Economic Sustainability

A sustainable transport system is by definition affordable. That is affordable to the businesses and individuals who wish to use it. A sustainable transport system must also reliably facilitate good access to a range of destinations (amenities, work places etc.), thus facilitating economic activity (Mihyeon & Amekudzi, 2005). Transport plays a pivotal role in supporting economic growth and balanced regional development. On the negative size, at a local level congested transport and a lack of transport infrastructure is associated with difficulty finding work, local economic decline, and neighbourhood social problems (Downs, 1999)

Resource exhaustion is also a significant concern to economic sustainability. At a local level, rising fuel prices may adversely impact individual disposable income and economic performance due to heavy reliance on private cars (Ruel, Garrett, Hawkes, & Cohen, 2010). On a global level, uncertainty about the long term future of oil resources has led to worldwide geo-political

instability which has far reaching economic and social consequences as governments struggle to secure and conserve resources.

There has been much speculation about the status of world oil reserves. This remains a contentious issue, polarised between advocates of peak oil who believe production will soon decline, and major oil companies that say that with new extraction technologies there is enough oil to last for decades. Data surrounding the issue is clouded the partisan nature of the debate. Political and business motivations have led to both the overstatement and understatement of remaining oil reserves. Technical issues regarding both the quality of oil remaining and technologies for extraction also hamper realistic discussions of the problem.

Owen, Inderwildi and King (2010) examined the status of conventional world oil reserves. They concluded that while there are certainly vast amounts of fossil fuel resources left in the ground, the volume of oil that can be commercially exploited at prices the global economy has become accustomed to is limited and will soon decline. Graefe (2009) reached a similar conclusion stating that the supply of energy as we have known it is in the process of transition. Today's "easy" conventional oil that the world relies upon as a primary energy source is being depleted, and, regardless of the exact timing of peak oil production—be it this year or fifty years down the road— the world faces the challenge of adapting to a new model of energy supply.

In many ways however, this debate is largely irrelevant to the Irish transport situation. Like many nations Ireland has no native supply of oil, leaving it vulnerable to international events (Gupta, 2008). There is also continuous international pressure to reduce CO_2 emissions (e.g. Oberthür, et al., 2010; United Nations, 1997). There are therefore many reasons for Ireland and other nations to pursue reductions in fossil fuel use by reducing the usage of private vehicles.

1.5.3 Social Sustainability

Though of less interest to this research than environmental and economic sustainability, social sustainability is still of importance when understanding the wider impact of the behavioural shift analysed. This section therefore briefly explores the link between transport and social sustainability. In general social sustainability is less well defined than either economic or environmental sustainability. Perhaps as a consequence of this, appropriate indicators are similarly poorly defined. The analysis of and improvement of social sustainability focuses on issues surrounding liveability and quality of life such as social mobility, living conditions, safety, security,

equality, justice, accessibility, provision of services etc. Human behavioural patterns with respect to sustainability may also fall under the remit of social sustainability.

Social sustainability can be examined at two levels, that of the individual wellbeing and the wellbeing of the community as a whole. Stiglitz , Sen and Fitoussi (2010) stated that wellbeing is multi-dimensional and identified eight key dimensions: material living standards (income, consumption and wealth); health; education; personal activities including work; political voice and governance; social connections and relationships; environment (present and future conditions); and insecurity, of an economic as well as a physical nature.

Wellbeing at a community level is associated with attributes people value about a place that contributes to the experience of "good life" and/or high "life quality". They are related to those natural or physical qualities and characteristics of an area that contribute to people's appreciation of its pleasantness, aesthetic coherence and cultural attributes. Such qualities can be tangible and measurable like noise but also less tangible like people's perceptions and attitudes. Noisy and polluting transport has been found to aggravate health problems.

At an individual level, the ability to travel safely, quickly and cheaply to a range of destinations can affect these correlates of wellbeing, e.g. the ability to access a range of employment opportunities. Stressors in the local environment during daily travel are also likely to affect an individual's mood and cumulatively impact on an individual's overall sense of wellbeing. Thus in travel patterns indicators of lifestyle patterns that foster and are fostered by high levels of wellbeing may be apparent.

1.5.4 Collaborative Consumption and Transport

New businesses based on allowing collaboration are being set up regularly. They operate in many market places and at both national and international scales. The renting/sharing forms of collaborative consumption (as opposed to the trading/swapping forms) works best where products have a high cost but a significant amount of idle capacity, i.e. a significant amount of time when they are not being used.

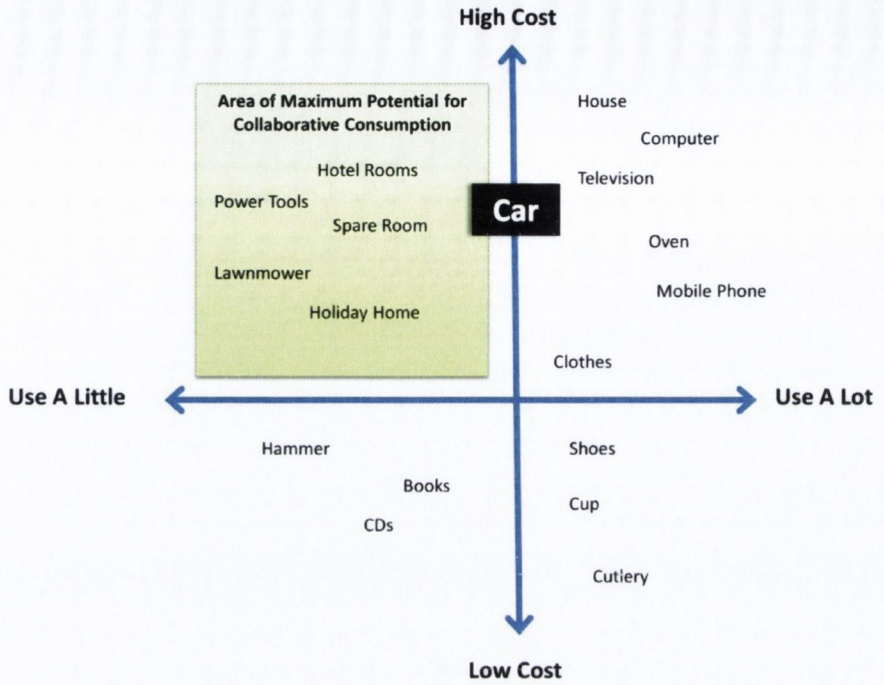

Figure 1.3: Illustration of When Collaborative Consumption Works (based on Gansky (2010))

This is illustrated in Figure 1.4, where products in the top left of the diagram are considered those best suited to collaborative consumption. Cars often fit these criteria. Cars have two forms of idle capacity, the times when they are not being used and empty seats when they are in use. Both of these forms of idle capacity offer an opportunity for companies using the collaborative consumption business model to facilitate the rental of this idle capacity.

1.6 Research Objectives, Aims and Design

This section provides an overview of the principle objectives and aims of this research. It then provides a description of the research design both as first designed and as implemented.

1.6.1 Research Objectives

The theme of this thesis is to investigate sustainable transport solutions with a particular focus on reducing reliance on private vehicles. Based on the concepts of sustainable development, ride-sharing and car sharing are collaborative consumption techniques which offer a possible way to improve the sustainability of transport while reducing reliance on private vehicles. Of particular

interest is the fact that these techniques offer the possibility of maintaining an individual's access to private vehicles while reducing overall reliance on them.

The objective of this thesis is therefore to investigate the impact of car sharing and ride sharing on environmental and economic sustainability indicators. The broad objective can therefore be narrowed to two narrower objectives:

- To enhance understanding of the potential of car sharing
- To enhance understanding of the potential of ride sharing

1.6.2 Research Aims

Using Dublin as a case study, this thesis evaluates the potential economic and environmental impacts of two proposed methods of reducing reliance on private cars – car sharing and ride sharing. When seeking to reduce the environmental and economic impacts of travel in private cars it is important to consider also the third pillar of sustainability, the social pillar. Therefore this thesis also briefly investigates whether the proposed reduction in reliance on private vehicles is likely to unduly negatively impact the social realm. Four aims are therefore identified:

1. To conduct a detailed literature review in the following areas:
    a. Car Sharing,
    b. Ride Sharing,
2. To achieve a better understanding of the relationship between an individual's travel pattern and a) their spending on domestic travel, b) the environmental impact of their domestic travel and c) their wellbeing.
3. To investigate the potential of car sharing in Dublin to reduce reliance on private vehicles while improving economic and environmental aspects of transport.
4. To investigate potential of ride sharing in Dublin to reduce reliance on private vehicles while improving economic and environmental aspects of transport.

1.6.3 Original Research Design

The original scope of this study was to evaluate how members of carsharing change their overall levels of sustainability, as measured by economic, social and environmental components. This holistic approach was unique in the research. The method chosen was to conduct a initial survey of members of an Irish car sharing service and those interested in joining an Irish car sharing service. This survey was to be repeated at an interval of one year, and in-depth interviews were planned with new and existing members of the car sharing service. Similar supplementary studies were also to be carried out in co-operation with European partners.

Of particular interest to the research were the second order effects of changes to levels of economic, social and environmental capitals. For instance, should respondents be found to save money by participating in car sharing, that money is likely to be spent on other things, e.g. consumer goods, holidays. This additional spending has its own environmental and social impacts, which though less important than the first order effects, have the potential to be significant.

The survey was designed and distributed in line with these original goals. The purpose of the survey was to assess respondents travel patterns and relate these to a selection of economic, social and environmental indicators. The survey hypotheses have were developed in the context of the discussion on sustainability presented in section 1.3 and section 1.4 and the known impacts of car sharing found in the literature review (Section 2.2). They were:

- On average users of car sharing schemes reduce their transport carbon footprint
- On average users of car sharing schemes reduce their transport costs
- On average users of car sharing schemes reduce their transport time costs
- On average users of car sharing schemes increase the time they spend being physically active
- On average users of car sharing schemes increase their sense of wellbeing

Originally Planned Studies

The survey itself was to be the primary research instrument on which other studies were based. The survey was been deliberately designed with European collaboration in mind, though some localisation was required. Tentative efforts to recruit additional research partners in Europe demonstrated a reasonable level of interest. Preliminary contact was made with a number of potential European Partners. These included:

- Whip Car in the UK
- Car Plus (UK)
- Cambio (across Europe)
- The Danish Car Sharing Foundation (Denmark)
- City Car Club (Finland)

A longitudinal component was also planned. A feature of the survey software (Schmitz, 2012) allowed tokens to be used to track specific responses. This was to enable the matching the responses of respondents who answer the survey again after a time has elapsed. The survey also specifically asked respondents whether they were willing to participate in follow up surveys and studies. It was planned that respondents would be asked to repeat the survey in one year's time allowing change in travel behaviour over a time period to be monitored.

Furthermore the Irish car sharing service, GoCar, had offered the researcher the opportunity to interview new members during the orientation. New members of GoCar are met by a member of staff and given an introduction to the service which includes checking of documents and a handover of the key card. Interviews were to be undertaken with willing new members of GoCar using structured interview techniques and allowing the exploration of the second order effects of car sharing.

This avenues of research described above depended very much on the findings of the first issue of the survey. As will be seen in section 3.5, the response rate from GoCar members was lower than expected. In addition to this the usage rates reported by the GoCar members who responded to the survey were very low. The original research design could therefore not be used and was adapted to facilitate further research.

1.6.4 Final Research Design

The failure of the initial survey to garner responses from members of GoCar prompted a re-examination of the car sharing literature review (described in Section 2.2) and the authors own conversations with car sharing industry experts.

This reflection highlighted a second research gap, that of the potential of car sharing, and as a corollary the potential of other collaborative consumption transport services. This research gap is discussed in detail in Section 2.5, however in brief, while several studies have been conducted on the impact of car sharing services on their members travel habits, little was known about the maximum full potential impacts if car sharing was made available to a wider population. A second collaborative consumption transport service, ride sharing, was also identified as suffering from a similar research gap.

It was therefore decided to utilise the data from the survey, in conjunction with readily available population data and the findings of other researchers, to build a model of population uptake of carsharing and ridesharing.

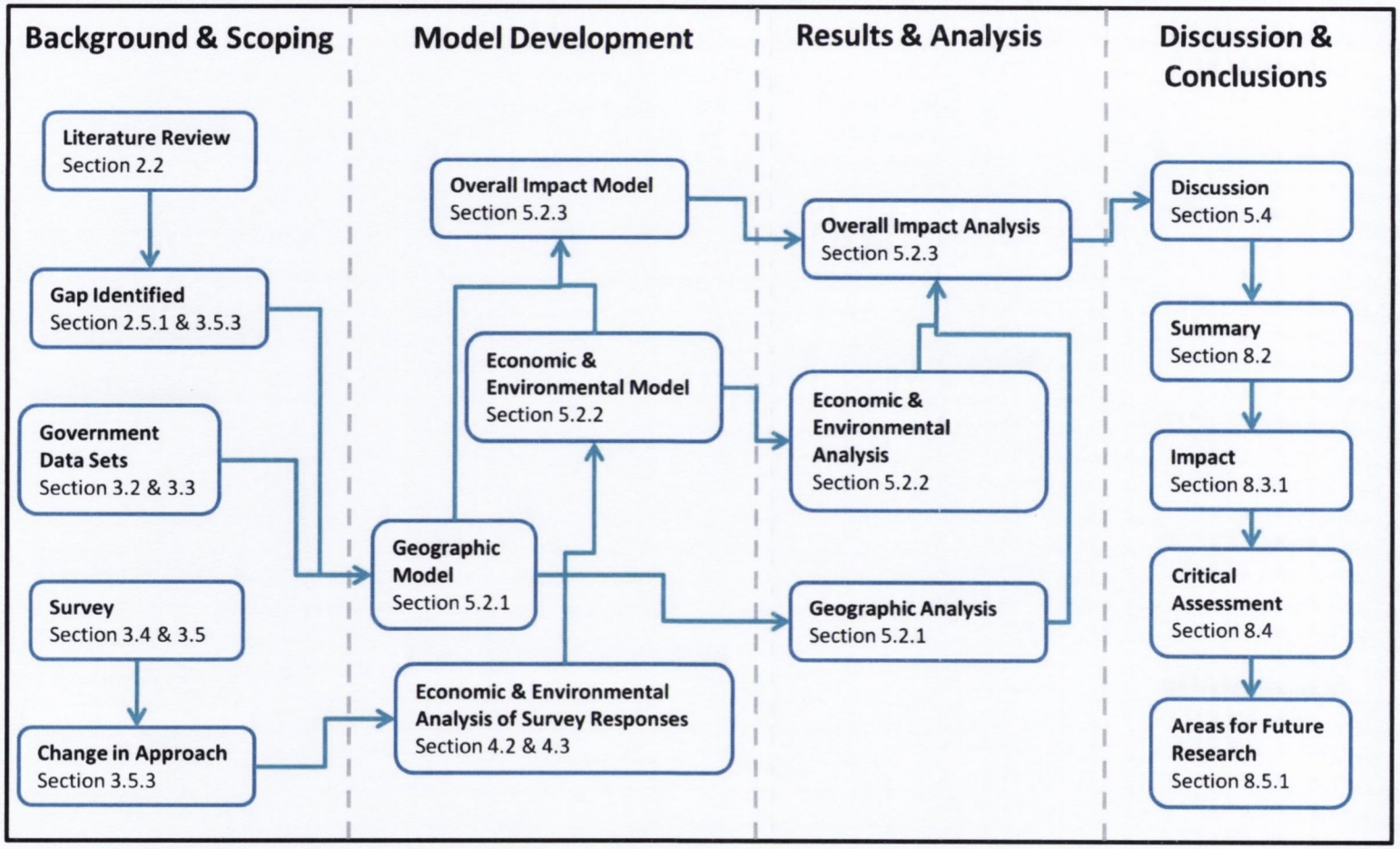

Figure 1.4: Flowchart of Car Sharing in Thesis

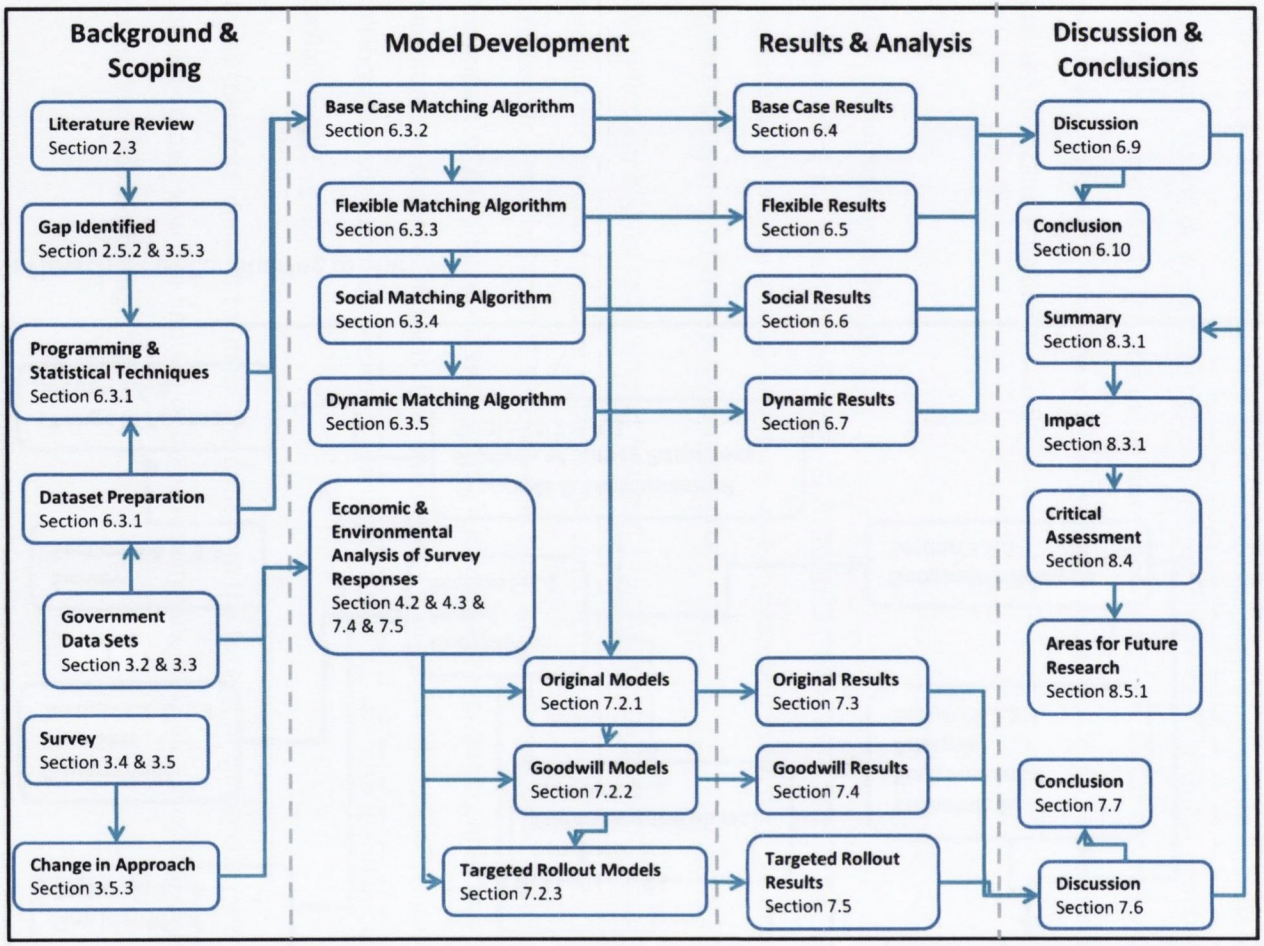

Figure 1.5: Flowchart of Ride Sharing in Thesis

A four stage research design resulted: background and scoping, model development, results and analysis and discussion and conclusion. The background and data acquisition phase described in section 1.6.3 was largely used for this work. Separately for ride sharing and car sharing models of the behavioural change were then developed. These models use overlapping data sources, but separately evaluate the likelihood of participation in each service and the consequent economic and environmental impacts. The behavioural change models are then applied and the results separately analysed. Conclusions about the potential impact of each service are then drawn and discussed.

These four stages are illustrated by the flowcharts provided in Figure 1.5 and Figure 1.6. The figures also identify in which section of this thesis the relevant part of the research is contained. A more general overview of the structure of the thesis is provided in Section 1.7 and Figure 1.7 below.

1.7 Structure of Thesis

This section briefly outlines the structure of the thesis. As stated in section 1.1 the potential impacts of introducing two methods of reducing reliance on private cars to a population are evaluated. These are car sharing and ride sharing. The remainder of this thesis is structured as shown in simplified form in Figure 1.7 and is described below.

The research to date relating to car sharing and ride sharing is discussed in detail in ***Chapter 2***.

Chapter 3 then describes the datasets and the additional data collection methods used to carry out this research. Datasets used include the Small Area Population Statistics and the Place of Work, School or College – Census of Anonymised Records. Both these datasets are derived from the results of Census 2011. Chapter 3 also describes the development and distribution of a comprehensive travel survey which was administered to 2,639 individuals around Ireland.

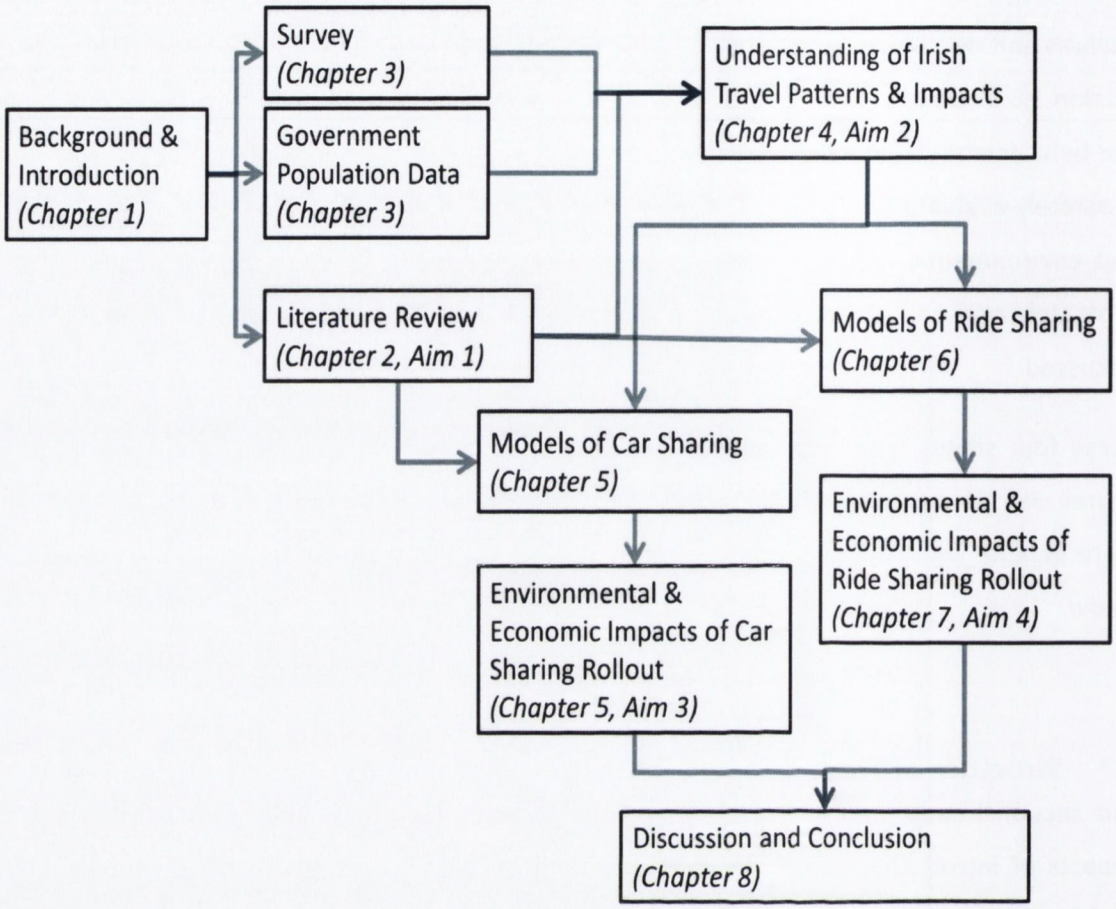

Figure 1.6 Structure of Thesis

Chapter 4 presents the investigation of individual travel patterns in Ireland. This is based on results of the survey. This chapter includes an analysis of the responses which calculates a cost of travel and carbon dioxide emissions of travel for each respondent. It also presents research work on social sustainability and transport. This work examines the link between private vehicle ownership and usage and individual wellbeing. The analysis investigates whether the reductions in reliance on private cars, resulting from car sharing and ride sharing, could have a negative impact on indicators of social sustainability.

Chapter 5 presents the research work on car sharing. It first describes the three stage methodology developed to carry out the evaluation of the environmental and economic impacts of car sharing. The results of the analysis are presented as a geographic analysis of population uptake, and an economic and environmental analysis of individual changes to costs and carbon dioxide emissions of travel. Using scenario based forecasts; these two analyses are then combined

to provide a full analysis of the environmental and economic impacts of the development of a car sharing service in both the Dublin area and across Ireland.

Chapter 6 presents the first phase of the research work on ride sharing. This chapter analyses the parameters affecting the number of matches a ride sharing service matching morning car commuters in the Dublin area might achieve. It first describes the development, in four stages, of a model which functions as a ride sharing service. In sequence, these are the Base Case Matching Algorithm, the Flexible Matching Algorithm, the Social Matching Algorithm and the Dynamic Matching Algorithm.

The Base Case Matching Algorithm matches an equal number of drivers and passenger subject to constraints related to the number of passengers per driver, the distance between driver and passenger origins, the distance between the driver and passenger destinations and the difference between the driver and passengers desired arrival times.

The Flexible Matching Algorithm extends the base case matching algorithm by varying the number of drivers with respect to passengers and allowing some individuals to adopt a flexible role, i.e. to act as either a driver or passenger.

The Social Matching Algorithm then extends the Flexible Matching Algorithm by modelling how passengers and drivers might accept or reject matches based on their similarity.

The Dynamic Matching Algorithm also extends the Flexible Matching Algorithm by allowing registrants to enrol in the service and receive matches in smaller groups (batches). This algorithm mimics how a ride sharing service based on a smart phone app might operate.

The chapter first describes the algorithms in full and then presents the results of the analysis of each model in sequence.

Chapter 7 uses the analysis carried out in Chapter 6 to model the environmental and economic impacts which would occur should a ride sharing service successfully operate in the Dublin area. In the first section it models the results of Chapter 6. In the second section it introduces more complex population behaviour. The model is extended so that those who successfully achieve a match continue to seek matches while those who do not achieve a match are less likely to participate. In the final part of this chapter a targeted rollout is tested. In this analysis, the population who participate is restricted to those who meet specific criteria, i.e. that they work within a designated boundary.

The final chapter, ***Chapter 8*** concludes the thesis with a summary of the key findings of the research and the contributions to knowledge. This chapter also discusses the shortcomings of the research and identifies the topics which require further investigation.

2 LITERATURE REVIEW

2.1 Introduction

This chapter provides a brief overview of the literature covering the three areas of interest to this research, namely car sharing, ride sharing. To support material presented in Section 4.4, it also provides a brief overview of the literature on the links between transport and social sustainability. It concludes with a summary of the gaps in the research identified by the literature review and addressed in this thesis.

2.2 Car Sharing

This section will discuss the research on present status of car sharing, focusing on the features of car sharing services (CSS) currently in existence, the sustainability impacts of car sharing (CS), on identifying the type of people who join a CSS, and the drivers and barriers to the adoption of car sharing. As stated in Section 1.1, in this research, by Car Sharing we mean the model of car rental where members rent cars from convenient points on a short term basis i.e. minimum rental periods are typically half an hour.

This definition is based on two definitions of car sharing, that provided by Millard-Ball (2005) who defined car sharing as follows:

> *"Car-sharing is a service that provides members with access to a fleet of vehicles on an hourly basis. Members reserve a car online or by phone, walk to the nearest parking space, open the doors with an electronic key card, and drive off. They are billed at the end of the month for time and/or mileage."*

and that provided by Shaheen, Cohen, & Chung (2009) who defined car sharing as follows:

> *"Carsharing organizations (or short-term auto use) provide members access to a fleet of shared vehicles on an hourly basis, reducing the need for private vehicle ownership"*

2.2.1 Background

Car sharing provides members with access to a car without the attendant capital costs. Variants of car sharing as a phrase include car-sharing and carsharing. The term car club is also commonly used to describe the service provider, particularly in the UK.

A car sharing service provides (1) a car to (2) a member for (3) a specific booking at (4) a price. These four components, their possible characteristics and how a car sharing service differs from a more traditional car rental service will now be discussed in turn.

The key characteristic of the first component the car is from where it is available. In a conventional rental car service, cars are available from a limited range of locations (e.g. Hertz, n.d.). Pick up and/or drop off from a location convenient to the renter incurs additional charges. In contrast car sharing services offer distributed vehicles which are available at locations convenient to the user. Barth and Shaheen (2002) identify three distribution strategies which a car sharing service may use: neighbourhood cars, station cars and multi-nodal cars. Neighbourhood cars are placed in locations convenient to the members' home and work locations. Station cars are placed at public transport nodes to extend the range of public transport thus facilitating its use. Multi-nodal cars are available to make one way journeys between a number of designated nodes.

The second component of the system is the Car Sharing Member (CSM) or user. For a conventional car rental service, any individual who meets basic age and licensing requirements can reserve a car (e.g. Hertz, n.d.). In contrast a car sharing service restricts rental to members who have registered in advance and who pay an ongoing subscription (e.g. Zipcar, n.d.). The characteristics of the members are a critical influence in the successful development of a car sharing service. Research on the personal and household characteristics of members of existing car sharing services will be discussed in the next section.

The third component of the system is the booking itself. Typically a conventional car rental service leases cars for periods of 24 hours and these reservations must be made in advance (e.g. Hertz, n.d.). Full payment for the service is expected in advance. A car sharing service rents cars for short periods of time, typically charging per hour or less of usage. While members may be billed at the time of reservation, billing on a monthly basis is also available (e.g. Zipcar, n.d.).

The final component of the system is the price paid. A conventional car rental service charges a fixed fee per day for use of the car (e.g. Hertz, n.d.). In some circumstances an additional fee may be incurred for high mileage usage. Fuel is an additional cost paid by the renter. In contrast typically members of a car sharing service pay a monthly membership fee to the service provider, a per hour fee and/or a per km travelled fee. Fuel costs are included in the price of vehicle rental (e.g. Zipcar, n.d.). A minimum period of membership may also apply.

2.2.2 Personal, Household and Travel Characteristics of Car Sharers

A literature review was carried out to identify the typical personal and travel characteristics of the members of car sharing services around the world. While there is some variation between CSS's based on the areas they target and the marketing strategies they adopt, a number of key generalisations can be made. Two large studies and a number of small studies have thoroughly investigated CSM's and their motivations for joining. These are now described in detail.

A large scale study was carried out by Martin and Shaheen (2010) and it focuses on the characteristics of CSM's in North America, including the United States and Canada. The results of this study have been published in full as: Greenhouse Gas Emission Impacts of Carsharing in North America Final Report (Martin & Shaheen, 2010) and a number of additional papers have been published which summarise aspects of the results (Martin & Shaheen, 2011a, 2011b, 2011c; Martin, Shaheen & Lidicker, 2010).

Martin and Shaheen (2010) described those who are mostly likely to join a CSS. Of the 6,263 (cleaned) responses to their survey of CSM's, they found that young adults were over represented with 56.6% of CSM's falling in the 25 – 40 age range, 35.8% of CSM's were over the age of 40, and the remaining CSM's under the age of 25. Education levels were also high within the respondent group, with 43% of CSM having a Bachelor's degree, and a further 39% having a higher degree. Females were also over-represented at 57% of respondents. CSM's lived in households that were smaller than the US average, at 1.9 persons/household. The median household income for respondents was $60,000, and the most common bands were $20,000 - $30,000, $30,000 - $40,000, $40,000 - $50,000, and $50,000 - $60,000, each of which contained approximately 10% of the sample.

Martin & Shaheen (2010) also found that 62% of households joining car sharing owned no cars and 31% of households owned one car. After joining car sharing 80% of households owned no cars and the total number of cars owned by all households was reduced by 50%. Most of this reduction (83%) came from one car households selling their only car. When asked about their primary reason for joining the CSS, 51% of households indicated that "My household did not have a car, but joined car sharing to gain additional personal freedom" and a further 14% indicated that they "owned one car, but joined car sharing and got rid of the car".

A second large scale study was carried out by Loose (2010). He reports the results of the *momo*[2] car sharing study, which was funded by the European Union and investigated car sharing as an

[2] An EU funded research program - More Options for Energy Efficient Mobility through Car-Sharing

option for energy efficient mobility. Overall the patterns found by the *momo* study in Europe are similar to those found by Martin and Shaheen (2010) in North America. Loose (2010) found that consistently across Europe, the majority of customers were between the ages of 26 and 49 and had Bachelor's or higher degrees. Those under 26, over 60 and those possessing only second level qualifications were found to be under-represented. In contrast to the North American study, the European study found that men were more likely to be CSM's than women, with proportions ranging from 53% - 69% for different CSS's across Europe. Loose (2010) does not report on the household income of CSM's, however the study does indicate that over 70% of customers are employed or self-employed in CSS's across Europe. As with North America, one and two person households were found to predominate.

Loose (2010) also reports that that in Europe the overall proportion of car sharing households without a car was between 52% and 92%, with most CSS's reporting figures above 70% and the proportion of households without a car being significantly higher than the population average in each case. 27.3% of CSM reported selling at least one car after joining the CSS.

In an early, smaller scale study, Steininger, Vogl and Zettl (1996) identify the characteristics of pioneer members of a CSS in Austria. While this research was conducted at a time when CSS's were still in their infancy and before modern technology facilitating service usage was readily available, the findings are still of interest today. Their findings are similar to those of later studies, that members were highly educated professionals towards the beginning (age 24-40) of their professional careers. Steineger et al. (1996) also found that 52.5% of members did not own cars prior to joining the CSS.

Cervero (2003) reports on the first year behavioural change of a CSS operating in San Francisco, California. This study was carried out 9 months after City CarShare was established. Cervero found that most members had not previously owned cars. As a result, the introduction of the CSS increased car travel, particularly for non-discretionary non-routine travel. At the two year mark, a follow up study was carried out by Cervero and Tsai (2004). This identified a different member profile, with 30% of members having sold at least one car as a result of joining the CSS. A further 2/3rds of members indicated that they had opted not to purchase a (an additional) car as a result of the CSS.

In all of the studies described above, the car sharing services provide either neighbourhood or station cars as described in section 2.2.1. That is CSM's must return the car to the location from which they began their journey. Due to problems with vehicle distribution and the need to

relocate cars, one-way or multi-nodal car sharing services remain rare and an evaluation of the personal characteristics of users of such car sharing services in not possible, however an early assessment of one scheme in Ulm, Germany (Firnkorn & Müller, 2011) suggests that such services may be capable of attaining greater market penetration than those currently in operation.

In summary, the research to date shows that CS appeals to specific segments of the population, particularly those who are highly educated, aged between 25 and 49, live in a one or two person household, and are working or self-employed. While most members join a CSS to gain access to a car, this access appears to delay or prevent the purchase of a private car. A significant proportion of households also reduce their car ownership levels upon joining. A CSS is mostly likely to attract early career urban dwellers that do not need a car to access work, or for regularly familial duties.

2.2.3 Potential Impacts of Car Sharing

At an individual level, a change in personal travel behaviour is the most direct and observable short term impact that occurs upon joining a CSS. These individual changes in travel behaviour result in larger scale population level impacts. While large scale studies, in particular that of Martin and Shaheen (2010) have examined the environmental impact of joining a CSS on individuals, few studies have addressed either the economic impact or the possible impacts if car sharing was to become more widely available.

Car sharing services provide members with access to cars on an as needs basis. For members this provides the benefits of car ownership without the purchase and annual costs, but at a higher price and inconvenience for individual journeys. The nature of the impact depends greatly on whether membership of the CSS is associated with an increase or a decrease in access to car travel.

Where membership is associated with an increase in access to car travel, typically the individual or household did not have access to a private car before joining the CSS. Martin and Shaheen (2010) investigate the greenhouse gas emissions impact of travel lifestyle changes that take place as a result of joining a CSS in these circumstances. They find that these households increase their green house gas emissions of travel on joining the CSS service, typically by between 0-250kg/year. These households typically joined the CSS as a substitute for vehicle acquisition, and based on the survey responses collected by Martin and Shaheen (2010), the study concludes that these households would report higher emissions in the absence of a CSS.

Where membership is associated with a decrease in access to car travel, typically the individual owned a private car before joining the CSS, and sells it upon joining. Martin and Shaheen (2010) also investigate this membership group. They found that that cars shed by US households joining CS were driven an average 21,250km in the year prior to joining car sharing, however fewer than 20% of all CS members drive more than 3,230km in CS vehicles each year, and 46% drive fewer than 800km per year.

Across both member types in Europe, Loose (2010) found that the average private customer drove 737km in a CS vehicle in 2008. In the US, Cervero and Tsai (2004) found that 6.5% of members' trips and 10% of their vehicle miles travelled were in were in CS vehicles. Based on the same survey data as their 2010 study, a further study by Martin & Shaheen (2011b) examines the effects of CSS membership on the modal split of members' journeys. They find a mixed pattern of increases and decreases in usage of each mode, and while a breakdown by reasons for joining is not provided, the study concludes that the "large and consistent difference in average vehicle kilometres travelled change suggests that those increasing and decreasing their public transit use were not randomly distributed, but rather a function of the prior circumstances under which they joined."

When all CSS members were evaluated together Martin and Shaheen (2010) found that on average, individuals joining a CSS reduce their CO_2 emissions of transport. Those who join CS to maintain some access to a car, considerably reduce their travel in cars and consequently their CO_2 emissions. Those who join CS to increase access to cars, tend to increase their travel in cars and consequently their CO_2 emissions. However this increase in CO_2 emissions is considerably lower than the increase in CO_2 emissions associated with car purchase.

These personal changes in travel behaviour also have wider impacts on local communities and economies, for instance increased levels of public transport use may require greater investment in public transport infrastructure and a reduced level of private car ownership reduces demand for parking spaces. Collectively the individual changes in CO_2 emissions and spending on transport may have larger scale effects.

A study on CSM's usage of a CSS (Morency, Trepanier, Agard, Martin, & Quashie, 2007) reveals information about when and how frequently members use the vehicles available. Morency et al. (2007) study the transaction dataset from 119,900 trips taken by members of a CSS operating in Montreal, Canada, in order to identify characteristic user behaviours. Using data mining techniques (k-means clustering and hierarchical ascending classification) they show that CSM's

can be classified using clustering techniques. The most important distinction they identify is based on members frequency of use. They find that the majority of members (over 90%) are occasional users, who use the service less than once per week, and make most of their journeys on Fridays, Saturdays or Sundays. The remaining users are frequent users, and these members are more likely to use the service on weekdays.

Duncan (2011) examined the cost saving potential of car sharing at a population level. His research focuses on two questions. These are: what kind of vehicle usage patterns can a CSS accommodate in an effective manner, and how many vehicles in the San Francisco Bay Area have usage patterns suitable for car sharing. He develops scenarios based on responses to the Bay Area Travel Survey 2000, with which to answer these questions. He finds that a CSS has the potential to effectively meet the needs of those who do not use their car to commute to work and that if the CSS was extended to all suitable census tracts in the Bay Area that up to 13.0% of households could reduce their cost of travel in private cars. Duncan's (2011) work however focuses exclusively on households which own cars and does not address potential members who don't own cars at the time of joining the CSS.

Le Vin, Lee-Gosselin, Sivakumar, and Polak (2014) also examine the potential of car sharing using the population of London as a case study. They apply an innovative forecasting technique to the population of London. The forecasting technique combines a stated choice survey (n=72) with a scenario based analysis to calculate the potential number of car sharers in London. Le Vin et al. (2014) predict a total market of 430,000 car sharers in London (population 8.2million) if a round trip service is fully rolled out and a market of 1,570,000 car sharers for a point to point service.

In addition to identifying the characteristics of pioneer members, Steininger et al. (1996) examine the size of the market segment and change in behaviour that occurred as a result of individuals joining a CSS. They selected six criteria to identify potential pioneer members – age 25-43, highly educated, owner of a low value car on which less than 15,000km is travelled per year, fewer than 33% of trips by car and participation in an environmentally proactive action. Using a survey based in Austria, they concluded that an average of 13.5% of household in urban areas met these criteria and were therefore potential immediately attainable CSM. However a subsequent invitation to 1200 households to join a CSS for a two month test phase without monthly payment yielded 18 households willing to participate, a 1.5% market segment.

These 18 households then participated in the CSS for a period of two months, and complete pre-membership and week 7 membership travel diaries. It was found that those who resided in

households which owned cars reduced the km/week they travelled in cars by 61.7% (192.9km/week) during the study. In contrast those who resided in household which did not own cars increased their travel in cars by 117.9%, however this increase reflects an increase from 25.7km/week to 30.3km/week.

In summary previous studies have principally examined the individual change in travel behaviour of those who have joined a CSS. These studies have found this change in travel behaviour has impacts on: a) the greenhouse gas emissions of travel, b) levels of public transport use, c) the times at which people travel, d) levels of private car ownership, e) distances travelled in private vehicles, and f) levels of cycling and levels of walking (Cervero, 2003, Cervero & Tsai, 2004; Loose, 2010; Martin & Shaheen, 2010; Martin & Shaheen; 2011b; Steininger et al., 1996).

CSM fall broadly into two types for whom the impacts of membership are different, these are:

- Those who join CS to maintain some access to a car, selling a car upon joining.
- Those who join CS to increase access to cars, to avoid the purchase of a (an additional) car

In both cases, a car owned by the household is not the primary mode of commuting to work. Overall a population with access to CS has a lower level of car-dependency and transport related carbon-dioxide emissions than a similar population without access to CS.

Car sharing is a good supplement to other modes of transport, however it is not suitable for all travel styles, household finances, residential locations or lifestyles for instance many people require access to a car to carry out their employment duties. Few studies have examined the number of individuals who have a travel pattern suitable for car sharing in the wider population.

2.2.4 Drivers and Barriers to Car Sharing

Car ownership confers many benefits to a household in particular flexibility of departure time and destination, and the ability to transport luggage and purchases. No other mode of transport confers these benefits (Beirão & Sarsfield Cabral, 2007). Car ownership has a large initial (purchase) cost and relatively large annual (insurance, tax) costs, however once these have been met, additional individual journeys are relatively cheap, generally incurring only fuel costs. Therefore, households which own a car typically use it frequently, even where other convenient modes are available. In short, when a household finds a car even occasionally necessary it will tend to purchase one, and once a household owns a car, it will tend to use it.

Enoch and Taylor (2006) conducted a worldwide review of support mechanisms for car clubs, aka CSS. Historically CSS have been formed both as commercial endeavours and as community level schemes sometimes run on a voluntary and/or non-profit basis. They identify several key barriers to the development of CSS, and foremost among these is a simple lack of understanding amongst national and local governments as to what a CSS is and how it might operate within an area. Enoch and Taylor (2006) identify three areas of government policy that have the potential to promote CS. These are regulation, fiscal mechanisms and information. Regulation includes measures such as the provision of parking, or the waiving of the need to provide parking spaces in a development where a CSS is available. Fiscal mechanisms may include tax breaks for CSS in the early phases of development, or financial support in the purchasing of cars or the installation of on street equipment and signage. Information support typically includes high level information from national governments disseminating information to local governments which supports the development of local level CS services, and the usage of established transport information channels (e.g. links with public transport providers) to disseminate information about car sharing.

At an individual level, drivers and barriers also exist. Of particular importance is the distance from a member's residence to the nearest car sharing station. In Europe Loose (2010) found that more than 80% of car sharing members live within 1km of a car sharing station. Therefore a key barrier to car sharing is whether potential members live within sufficiently close proximity of one another to enable a financially viable CSS to operate. This question has not been addressed in the literature to date.

2.3 Ride Sharing

The previous section discussed car sharing, in the context of two strangers sharing a car, owned by a CSS, and having no association with each other. In this section we discuss a different form of car sharing, where two or more individuals arrange to share a journey in a car owned by one of them. In Europe this is known as carpooling, car pooling, lift sharing and occasionally as car sharing. In Northern America this is known as ride sharing or ridesharing. To avoid confusion between car sharing and carpooling we adopt the North American usage throughout this research. The literature on ride sharing is now discussed.

Everyday people travel in cars with empty seats. This under-utilised resource offers an opportunity to improve the sustainability of transport by reducing CO_2 emissions, reducing congestion and reducing the cost of travel to individuals. It requires no additional expensive

physical infrastructure instead utilising spare space in cars which are already making the same journey.

2.3.1 Background

Morency (2007) proposes that ride sharing exists when two or more trips are executed simultaneously in a single vehicle. At the most general level ride sharing exists when two individuals share a journey by car. As with journeys undertaken using a car sharing service, ride shared journeys have a number of possible characteristics. These are (1) the individuals involved, (2) arranging to share (3) a common journey.

The first characteristic of the ride shared journey are the individuals involved, or more specifically their relationship to each other. This characteristic is intrinsically related to the second characteristic, how the arrangement to share the journey is made. At the two extremes of ride sharing are household ride sharing and hitch hiking. Ride shares that take place within a household are based on a long standing relationship, social obligation, the shared cost of vehicles and a detailed knowledge of each other's travel patterns and needs. This is further facilitated by a common origin point and frequently a common destination point when a shared activity is involved. Such journeys may be planned from months to seconds in advance of the departure time. At the end of the ride sharing spectrum is hitch hiking, where one person stands at the origin point and uses gestures or signage to indicate their need for a lift and a passing stranger

While individuals who know each other are most likely to ride share, this thesis investigates the potential of ride sharing when matching trips are identified with assistance from a third party service. Therefore as stated in Section 1.1, a narrower definition of ride sharing:

Ride Sharing: Two individuals, who are at best tenuously acquainted, using modern technology to arrange to share a common journey in a car which belongs to one of the individuals.

The literature also distinguishes between two approaches to arranging to ride share: static and dynamic (Agatz, Erera, Savelsbergh, & Wang, 2011; Levofsky, & Greenberg, 2001). Static ride sharing occurs when the arrangement to ride share is made in advance of the journey. Historically static ride sharing has been facilitated through initiatives such as workplace bulletin boards and school mailing lists. More recently static ride sharing is facilitated by traditional websites and by mobile internet devices. Dynamic ride sharing occurs when the arrangement is made close to or at the point of departure. It requires real time information about the locations of potential drivers and passengers and is best facilitated by mobile phone and GPS technology, though it can occur spontaneously as hitch hiking.

The third characteristic is the common journey however this seemingly simple component is complex when evaluated with respect to environmental policy goals. Morency (2007) distinguishes between two diametrically opposite forms of ride sharing: sustainable ride sharing and questionable ride sharing. Questionable ride sharing occurs when the driver is acting as a chauffeur for a passenger, making a solo return trip. Such ride sharing increases rather than decreases the distance travelled in a private car. Examples include household members making extra trips to drop and pick up each other, traditional taxi services and some web-facilitated ride sharing services e.g. Uber (Walton, 2014). Sustainable ride sharing, with which this thesis is concerned, occurs where two trips which would be undertaken in separate cars are combined in a single trip, sometimes requiring a deviation by the driver. The total distance travelled in a private vehicle is thus reduced.

2.3.2 Personal, Household and Travel Characteristics of Ride Sharers

Having defined ride sharing as happening between two individuals who are at best tenuously acquainted, a difficulty is encountered. Much of the literature does not distinguish between intra-household (members of the same household) and inter-household (members of different households) ride sharing. Furthermore typically non-household based ride share arrangements form between individuals who have some form of social or professional connection, most typically as work colleagues with a common destination and arrival time. However a social or professional connection is not a necessary pre-condition to ride sharing.

In Washington DC where reduced tolls for ride sharers offer a monetary incentive to drivers, spontaneous ride sharing arrangements occur regularly. Similarly in Houston and Los Angeles, reduced travel times through the use of car pool lanes incentivise drivers to offer strangers' lifts. Spielberg and Shapiro (2000) investigate the spontaneous formation of ride shares or "slugging" in Washington DC. Here the occupancy rules require that each driver has a minimum of two passengers in order to utilise the high occupancy vehicle lanes and it is common for drivers to stop at designated points to pick up random individuals seeking a ride. Spielberg and Shapiro (2000) find that the need for two passengers provides a sense of security and safety to both drivers and passengers, which facilitates the continuation of the practice.

Burris and Winn (2006) studied the characteristics of those participating in casual ride sharing in Houston, Texas. License plate data was used to identify and survey drivers using the car pool lanes in Houston. Surveys were also distributed to passengers at designated pick up points. Results of

the analyses revealed that commuters between the ages of 25 and 34, and working in professional/managerial or administrative/clerical occupations were more likely to ride share.

Several studies have also examined ride sharing generally, without distinguishing between inter and intra-household ride sharing. Vanoutrive et al. (2012) investigated the determinants of carpooling to work in Belgium. They considered three potential factors – the location in of the workplace, the promotion of carpooling to the workforce and the organisation of carpooling clubs within the workplace. They found that organisations with more employees had a higher proportion of ride sharers, and that locations which were less accessible (to public transport) had a higher proportion of ride sharers. They found other organisational factors to be not significant, except for except for the provision of a guaranteed ride home.

Caulfield (2009) examines the 2006 Place of Work, School or College – Census of Anonymised Records (POWSCAR) dataset for the 19,977 (3.75%) commuters working in Dublin who reported ride sharing as their primary means of travel to work. He develops a logit model which describes those individuals most likely to ride share as a passenger. He makes several findings, including that individuals are more likely to travel as passengers if they are female, part of a couple, live in a household with one car, in manual-skilled, skilled or unskilled employment and depart for work between 7am and 8am.

Unfortunately, the POWSCAR 2006 and 2011 datasets offers no information on the drivers with whom these passengers travel. Given the household characteristics described, it seems likely that many of the passengers described are participating in intra-household shares. To illustrate, an examination of the data in the 2011 dataset reveals that of the 15,906 individuals in Dublin who report travelling as a passenger to work, only 1311 report living in a household with no car. That is 8.2% of the passenger commuter population reside in a household with no cars Vs 12.5% of Dublin commuters reside in a household with no cars. Further information on the 2011 POWSCAR dataset is provided in Section 3.2 and Section 3.3.

2.3.3 Potential Impacts of Ride Sharing

Ride sharing is a Travel Demand Management (TDM) tool which has been used to reduce fuel demands, reduce congestion and more recently to reduce the environmental impact of car travel (Enoch & Zhang, 2012, pp.233-257).

Caulfield (2009) estimates the current benefits of ride sharing for the morning commute in Dublin. Using the POWSCAR 2006 dataset and the COPERT 4 model he estimates the CO_2 emissions saved

by ride sharing. He finds that between 7604 and 12,674 tonnes of CO_2 are saved annually by these ride sharers forgoing driving alone to work. This analysis however assumes that those sharing a car to their place of work are doing so in place of driving alone. They may instead be forgoing walking, cycling or public transit. They may also be engaging in what Morency (2007) describes as questionable ride sharing., i.e. the driver is not making a similar journey, but takes an extra journey specifically to facilitate the passenger.

The ability of ride sharing between strangers to reduce the environmental impact of travel depends first on the existence of appropriate matches, second on the willingness of individuals to use these matches and finally on the ability of individuals to identify appropriate matches. Identifying suitable matches is a key component of the successful promotion of ride sharing. A number of researchers have investigated whether sufficient appropriate matches exist, however this research has reached contradictory conclusions.

Tsao and Lin (1999) conducted a mathematical analysis of the potential of ride sharing. Their calculations use individuals working and living within grid squares of 2 miles by 2 miles, at uniform density of 660 jobs/square mile, a density roughly equivalent to that of Los Angeles. Origins and destinations are assumed to be at the centroid of each grid square. Based on these assumptions they concluded that carpooling had little potential to reduce congestion, as even without accounting for departure time differences few appropriate matches existed. However Tsao and Lin also acknowledge that car pooling in LA exceeds their predictions, because the distribution of workplaces is not uniform and because certain commuter routes are more likely than others.

Agatz et al. (2011) conducted a simulation study based on the 2008 travel demand model for the metropolitan Atlanta region. Assuming that each trip originates and finishes at the centre of one of 2,024 travel analysis zones, and a set of modelled departure times, they simulate a stream of trip announcements and seek to identify appropriate matches. The 2,024 travel analysis zones cover an area of 6,500 square miles (16,835 km^2) and approximately 5 million people. On average each zone therefore covers 8.3 km^2 and 2470 people.

Agatz et al. (2011) model the matching process by randomly generating streams of announcements. Each announcement is active for a certain period of time and the model adopts a rolling horizon approach, whereby matches are made at regular time intervals. For each announcement, a match is made between any rider and driver for whom a share is both time feasible and produces positive travel distance savings. A weight is applied to the match related to

the travel distance savings it generates. Commercial optimization software is used to identify the optimum set of viable matches.

Three variations on the model are tested. In the first each announcer adopts the role of either driver or passenger; in the second all announcers are willing to adopt the role of either driver or passenger. The third model is used to establish the advantage of optimisation based matching and it operates by having all announcers adopt a specific role, and matching those announcing as a passenger in order of arrival. They then investigate whether match rates sufficient to sustain a pool of ride sharers can be generated by modelling a probability of adoption for 4% of the population using a goodwill algorithm. In their model, 5% of the total trip announcements remain active and the success rate converges to approximately 85% of announced trips. There are a number of drawbacks to their model however.

On a smaller scale Amey (2011) uses real data from individual trips to estimate the potential of ride sharing within a university. Amey (2011) presents a methodology for estimating ride share viability using travel to and from the MIT campus as the basis for analysis. The model works by taking a sample population of 5,062 and generating journeys between each possible pair (25.6million) of commuter origins. Constraints are then applied to extract those pairings which are feasible matches. For larger populations this method of modelling is clearly unworkable, however the core approach: identify matches, reduce matches subject to constraints and then assign matches; is of interest to this research.

Šelmić, Macura, & Teodorović (2011) also investigate ride matching solutions to reduce the number of cars crossing a congested bridge. The solution they propose uses a K-means clustering technique to match individuals with even license plates (drivers) with multiple passengers who possess odd license plates. They characterise participants using a series of attributes related to their departure point, arrival point, departure times, arrival times and license plate. The K-means algorithm is then used to cluster participants subject to constraints related to the presence of at least one individual with each licence plate type in each cluster. Each cluster then becomes a "car", and shares the journey. The solution they propose can be optimised to reduce the inconvenience to participants by minimising their detour distances or to minimise the number of cars thus maximising the reduction in congestion. Thus the solution is flexible.

These theoretical attempts to model ride sharing (e.g. Tsao & Lin, 1999; Agatz et al., 2011) make assumptions about the detours ride sharers are willing to take in order to identify matches. The inconvenience they assume (detours of up to 3.2km), may be somewhat excessive, however aside

from the MIT study (Amey, 2011) there is no research which evaluates the level of inconvenience individuals must be willing to undergo in order to identify a match and how many matches exist in a real population at different levels of inconvenience.

2.3.4 Drivers and Barriers to Ride Sharing

Ferguson (1997) discusses the rise and fall of the American carpool in the period 1970 – 1990. He notes that historically, high rates of ride sharing are associated with points of crisis, most notably World War II and the 1970s oil crisis. Absent these conditions ride sharing declines rapidly to a small proportion of total mode share. Ferguson (1997) concludes that an increased number of vehicles on the road, falling fuel costs and increasing education among commuters were important factors in the decline of commuter ride sharing in the United States during the 1970 – 1990 time period.

The literature reviews a number of large scale ride sharing programs which have been trialled over the years. A number of academic papers summarise (e.g. Levofsky & Greenberg, 2001; Ghoseiri, Haghani, & Hamedi, 2011) these organized ride sharing initiatives. Without exception these ride sharing programs have been failures.

Giuliano, Hall, and Golob (1995) evaluated one such large scale scheme: the Los Angeles Smart Traveler. This was an ambitious project which used three different media approaches for providing traveller information: fully automated telephone systems, automated multi-media touch screen kiosks and PC via modem. The kiosks were placed in highly trafficked pedestrian locations (e.g. food courts) and offices however no individual or flyer was available nearby to explain their purpose or guide potential users. They were used so infrequently that Giuliano et al. (1995) calculated a cost per use of $2.00, higher than a traditional telephone information system. The automated telephone system was also little used, with 34 persons per week accessing the system. Though in its infancy, the internet based system attracted the highest usage rates with 400 uses per day. This system did not offer matches but did provide users with information related to traffic congestion.

Hall and Qureshi (1997) investigated the possibility that a user would be successful in finding a match using the Los Angeles Smart Traveler system. They designed an experiment whereby an individual with a workplace in downtown Los Angeles used the service to seek a ride for a semi-crisis situation (car break down or car under repair). Large employers in the Los Angeles area were required to register their employees with the ridematch service to meet air pollution regulations,

and this requirement provided a large database of approximately 500,000 users. The Smart Traveler system offered two methods of attaining a ride – automated and manual. With the automated system the requesting passengers records a voice message, the system then calls up to ten potential matches and plays the message. With the manual system, the system provides the requesting passenger with details of up to ten potential matches. The requesting passenger can then personally contact these matches. Several parameters were varied including the time of the requested ride, the home destination and the type of trip (round trip or one way. 42 rides were sought manually over a 40 day period between February and April 1995. 9% of manual calls resulted in an unconditional offer of a ride, while 11% of the calls resulted in a conditional offer (e.g. different departure time or route). For the 42 rides sought, 54.5% of cases resulted in the match seeker successfully obtaining a ride. 12 rides were sought automatically over the same time period. This resulted in 120 potential matches and just two conditional offers of a ride. For the 12 rides sought, 8.3% of cases resulted in a match seeker successfully obtaining a conditional ride.

Both the Hall & Quereshi (1997) and Giuliano et al. (1995) studies conclude that the telephone system was too complex and time consuming to use. Giuliano (1995) also finds that safety and security were key concerns for potential participants who when a ride share was required were generally able to find a satisfactory solution via their family, work colleagues and extended social network, i.e. there was little demand for the service offered.

Two small scale examples include the Bellvue Smart Traveler program and the Sacramento Rideshare Marching Field Operational Test. The Bellvue Smart Traveler program in Washington State matched ride shares within geographically based groups from November 1993 to April 1994. 53 users registered, 509 rides were offered and only six ride matches were logged. In Sacramento California, 360 people from a database of 5000 who expressed an interest in ride sharing, registered with the service. Ten requests were made for matches; one potential match was made however it is not certain whether this match was secured.

Ride sharing remains common in areas where severe congestion can be bypassed via High Occupancy Vehicle (HOV) lanes and where HOV's are subject to reduced tolls. (e.g. Washington DC, California).

Research and behavioural evidence suggests that the reluctance to rideshare, particularly with strangers is due to the loss of flexibility, the difficulty in finding suitable matches, and the lack of incentive to the driver.

2.4 Social Sustainability, Wellbeing and Transport

The second aim of this thesis includes the investigation of the relationship between travel patterns and individual wellbeing. This section therefore briefly outlines the literature which investigates this relationship.

Recent research into social sustainability has focused on the issue of individual wellbeing. In a definitive report, Stiglitz et al. (2010) evaluated the measurement of economic performance and social progress. Written with the express purpose of identifying alternatives to GDP as indicators of societal progress, this report considered three core issues: GDP, quality of life, and sustainable development. The report concludes that measurement systems should undergo a *"shift of emphasis from measuring economic production to measuring people's wellbeing".* It further defines current wellbeing as having: *to do with both economic resources, such as income, and with non-economic aspects of peoples' life (what they do and what they can do, how they feel, and the natural environment they live in" (*Stiglitz et al., 2010, pp.11-12). Linking sustainability with the concept of wellbeing, Stiglitz et al. (2010) state that sustainability is then achieved if the current level of wellbeing can be maintained by future generations.

Stiglitz et al. (2010) identify eight dimensions of wellbeing: 1) material living standards (income, consumption and wealth), 2) health, 3) education, 4) personal activities including work, 5) political voice and governance, 5) social connections and relationships, 7) environment (present and future conditions), and 8) insecurity, of an economic as well as a physical nature. These eight indicators reflect current understanding of the relationship between objective quality of life indicators, life circumstances and wellbeing.

As stated in Section 1.5 at travel facilitates participation in areas that contribute to wellbeing such as personal activities, social connections and relationships, access to healthcare, and work. Furthermore those who can travel quickly and easily to a range of destinations should find it easier to engage in these positive activities if desired, while less time spent travelling also leaves more time for these and other activities. An indicator of wellbeing is therefore used as an indicator of social sustainability.

2.4.1 Measures of Self-Perceived Wellbeing

At its core, wellbeing refers to contentment, satisfaction or happiness derived from optimal functioning. Despite general agreement that wellbeing is a subjective feeling state in which

positive feelings predominate, there is disagreement over more detailed ingredients of its definition.

While wellbeing has been discussed in the literature for some time, no single measurement technique has emerged as definitive. As will be seen in the review of literature specifically related to wellbeing and transport later, measures which have been used in transport have ranged from the simply ""How happy are you now?" (e.g. Leyden, Goldberg, & Michelbach, 2011) to complex multi-item questionnaires (e.g. Gee & Takeuchi, 2004).

In the wider literature, a number of researchers have conducted reviews of common measures of wellbeing (e.g. Henkel et al. 2003; McDowell, 2010; Primack, 2003). McDowell (2010) selects several single items measures and eight commonly used scales of wellbeing for comprehensive review. These were the Life Satisfaction Index, the Bradburn Affect Balance Scale, the Philadelphia Morale scale, the General Wellbeing Schedule, the Satisfaction with Life Scale, the Positive and Negative Affect Scale, The World Health Organization 5 (WHO-5) item wellbeing index and the Ryff's scales of psychological wellbeing. Each of these scales was assessed for reliability and validity. Mc Dowell found that the scales he considered each offered good or excellent reliability and validity, and that some (the Bradburn Affect Balance Scale, WHO-5 and the Satisfaction with Life Scale) were particularly suited to survey research.

Of these the WHO-5 Wellbeing index was selected for this study because it combines a high level of validity and reliability, an extensive existing body of research, a focus on the positive aspects of wellbeing, and a short easily implemented set of questions (Bech, 2004; Henkel et al. 2003; McDowell 2010). The WHO- 5 wellbeing test consists of five positively worded statements, for which respondents are asked to rate their feelings over the last two weeks, on a six point Likert Scale, from all of the time (5pts) to at no time (0pts) (Bech, 2004). The maximum score is 25pts, representing high wellbeing and the minimum score is 0pts. The five questions are:

1. I have felt cheerful and in good spirits
2. I have felt calm and relaxed
3. I have felt active and vigorous
4. I woke up feeling fresh and rested
5. My daily life has been filled with things that interest me

Several studies have found that subjective wellbeing is intrinsically linked with subjective health. For instance, Okun and George (1984) find that self rated health is the strongest predictor of subjective wellbeing during adulthood. Similarly, a meta analysis by Okun, Stock, Haring, and Witter (1984) of 104 studies carried out in the US prior to 1980 finds that health and subjective

wellbeing are significantly and positively related. The 2011 Irish Census (CSO, 2011a) included a question asking respondents to rate their health. The question asked respondents to self-report their health status, asked them to rate their health as excellent, very good, good, fair or poor. This is identical to the question used in the survey which was carried out as part of this research work (see Chapter 3).

The Central Statistics Office has published a study analysing the responses to the health question on the 2011 Census (CSO, 2011a). This study, entitled "Our Bill of Health" (CSO, 2012c) presents results regarding the general health of the Irish population. The results demonstrate that age and health status are closely linked, with only 30% of those aged 65-69 reporting Very Good Health. A link between social class and health is also discussed, with those in Social Class 7 reporting lower average health than those in Social Class 1. Under the age of 50, all groups report over 90% Good or Very Good Health; however in the over 50 age group, 87.1% of Social Class 1 report very good healthy, while less than 60% of those in Social Class 7 report the same.

Niedhammer, Kerrad, Schutte, Chastang, and Kelleher (2013) also evaluate the socio-demographic predictors of self reported health in the Republic of Ireland. Their analysis is based on a National Survey on Lifestyle, Attitudes and Nutrition which received 10,364 responses, which again used the same health question as that used in Census 2011 (CSO, 2011a) described above. Among the predictors of self rated health they identify are work status, education level, marital status (for men), low social support, neighbourhood problems (for women), low physical activity and absence of car (for women).

2.4.2 Wellbeing and Transport

There has been little direct research on the connection between travel-patterns and wellbeing. Typically researchers compare satisfaction with travel and transport disadvantage, with measures of psychological wellbeing (e.g. Bergstad et al., 2011; Delbosc, 2012; Delbosc & Currie, 2011)

Delbosc (2012) provides a detailed review of past literature on the topic of wellbeing and transport. Delbosc (2012) discusses the role of wellbeing in transport policy. She evaluates the hypothesis that transport can have a measurable impact on psychological wellbeing and suggests a model by which it can take place.

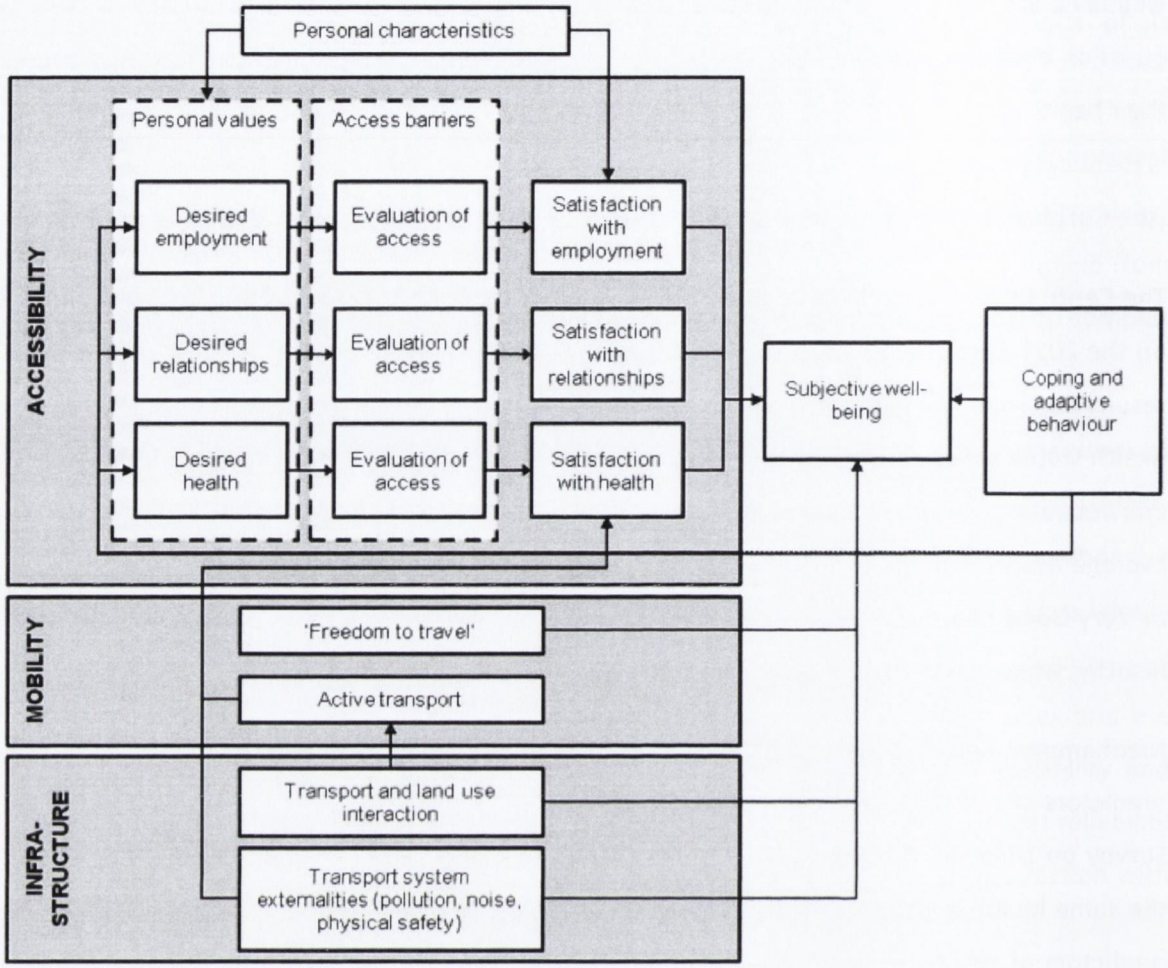

Figure 2.1: Delbosc's (2012) Theoretical Model of Transport's Influence on Subjective Wellbeing.

The conceptual model she proposes (presented in Figure 2.1) suggests that transport can influence subjective wellbeing through access to important activities, physical mobility and physical infrastructure, i.e. by enabling access to the most significant correlates of wellbeing identified in Section 2.4.1.

Delbosc's (2012) work also identifies some of the principle difficulties associated with exploring the link between transport and wellbeing. These include the selection of appropriate mobility and wellbeing indicators. Objective measures of mobility (e.g. number of trips) may not reflect a respondent's personality, i.e. one respondent may be content with one social visit to friends per week, while another that may desire three or more such visits. While better in some respects, subjective measures (e.g. are you happy with your bus service?) may be unduly biased by an individual's state of mind, regardless of their actual satisfaction with the transport service.

Leyden et al. (2011) assess happiness in ten major cities in order to explore what conditions of cities are associated with the happiness of residents. Leyden et al. (2011) find that convenient public transportation, accessible amenities, affordability and an environment suitable for raising children are conducive to happiness among residents. These findings are based on a quality of life survey conducted on ten major cities. Respondents were asked to subjectively rate their happiness on a five point scale (1 – Not Happy at all to 5 – Very Happy) in response to the question "How happy are you now?" Subjective responses were also used to assess each quality of life issue. For instance, public transport was assessed by asking respondents to rate from 5 – strongly agree to 1 – strongly disagree, the statement: "It is convenient to use public transportation (e.g. subways, trains or buses) in my city". The average score for those who rated themselves very happy was 4.07 while the average score for those who rated themselves Not Happy at all was 3.48. The use of two subjective indicators in this case is somewhat questionable. People who subjectively perceive their city in a positive way also subjectively perceive themselves as happier. This in itself may explain the findings made.

The study by Gee and Takeuchi (2004) uses both a subjective indicator (individually perceived traffic stress) and an objective indicator (ecologically measured vehicle burden) to examine the link between transport and general health status and depression. Health and depressive symptoms were measured using two well known indicators, the Medical Outcomes Study Short Form 36 and the Revised Symptom Checklist 90 respectively. Traffic stress was measured using Likert-response scale responses to questions regarding perceived environmental stressors. Vehicular burden was measured using census data, and was related to the number of individuals who drove or took public transportation to work within the relevant census tract. Using a hierarchical linear model, Gee and Takeuchi (2004) find that perceived traffic stress is associated with lower health status and more depressive symptoms, and that those who lived in areas with greater vehicular burden reported the most traffic stress, the lowest health status and the greatest depressive symptoms.

This hypothesis is supported by some studies on the elderly for whom car use is often provides a necessary level of access to community activities and independence. Ahern and Hine (2012) examined this issue among older people resident in rural communities in Ireland and Northern Ireland. Using focus groups, they find that due to the lack of alternatives, driving cessation has an extremely negative impact on the quality of lives of older people in rural areas.). In other studies of the elderly, it was found that mobility had an impact on quality of life; however other studies on the elderly found that there was a small and inconsistent relationship between time outside

the home and wellbeing (Spinney, Scott, & Newbold, 2009). Similar small and inconsistent results were found by other studies on adult populations, with the impact of transport on wellbeing being exacerbated by other factors such as unemployment, social exclusion lack of social support or other impairment (Delbosc & Currie, 2011; Stanley, Hensher, Stanley, & Vella-Brodrick, 2011).

Bergstad et al. (2011) use both subjective and objective indicators as measures of travel to investigate the link between subjective wellbeing and satisfaction with daily travel. This study is of particular interest as it focuses on car use. The survey of 1,330 Swedish citizens on which the study is based, included measures of car access, car use and satisfaction with performance of out-of-home routine activities. They find that car use has a marginal effect of subjective wellbeing, however they caveat their findings, stating that their findings do not necessarily warrant the conclusion that car access and use play no or little role in SWB and that a forced reduction in car use may still have a large impact on wellbeing.

Other studies have found that car ownership is correlated with higher income (Dargay & Gately, 1999) and that higher income is correlated with higher happiness (Blanchflower & Oswald, 2004). However car usage has been found to correlate with obesity (Frank, Andresen & Schmid, 2004), which is correlated with lower levels of wellbeing.

Farber and Páez (2009) conduct an analysis of car use and participation in social activities using a database of travel records from the 1994 Portland Household Activity and travel Behaviour Survey. Participation in social activities is often used as a proxy for social wellbeing. Farber and Páez (2009) divide their sample into three categories based on their level of usage of cars: automobile reliant (all journeys by car), mixed-auto (some journeys by car) and automobile free groups (no journeys by car). They find the three groups have similar socio-economic characteristics, but different demographic characteristics, e.g. the automobile group is more concentrated in 25-64 age range and is less likely to live in the urban core. To somewhat control for these differing demographic characteristics, they further subdivide the sample into suburban and urban respondents. They then examine the interaction between membership of each of the three automobile reliance categories affects the participation rates and duration of respondent's social activities. For all respondents (suburban and urban) they find that auto-mobile reliance is associated with lower levels of participation in social activities, both by minutes per day and by activities per day.

2.5 Discussion

This section briefly summarises the gaps in the literature identified as a result of the reviews carried out in Section 2.2, Section 2.3 and Section 2.4 above.

2.5.1 Gaps in Car Sharing Research

In September 2011, as the study of car sharing was beginning, the principal researcher on this PhD attended the final conference of the momo research project, entitled *"Street space for citizens: Car-Sharing replaces car ownership."* One of the major themes of the conference, which recurred even in seemingly unrelated presentations, was the potential of car sharing. While the participants as a whole were generally optimistic, the data and real world experience was open to a wide range of interpretation.

Car Sharing had existed for over 20 years and in Europe had a total membership of 500,000. In some respects this is high, however in comparison to the numbers using public transport, owning private cars or even simply using taxis, it is very low. In short, market penetration after so many years remained very low. Relatively recent improvements in information technology offered room for optimism; however as the literature and the experience of those operating a CSS show, CS is only suitable for those with a particular set of travel patterns and lifestyles.

In particular a comment in the conference "momorandum" stands out ("momorandum - calling the EC to support Car-Sharing (car clubs) | CORPUS", 2011). The statement "based on the number of car sharers in Switzerland, the EU27 could have 6,000,000 car sharers" is made with the footnote: "Switzerland has 100,000 car-shares in a population of 8 million. EU27 has about 500 million inhabitants." From both this experience, and the review of the literature described above, it was clear that a more rigorous method of estimating the potential of car sharing was needed.

While some examples found in the literature (e.g. Duncan, 2010; Steininger et al.,1996) attempted to address this question, on closer inspection problems are evident. Duncan's (2010) estimation does not include households which do not already own a car in the estimation of potential whereas Martin and Shaheen (2010) find that the majority of those joining CSS are members of households which do not already own a car. While Steininger et al.'s (1996) study does include such estimates; it is now almost 20 years old and both the costs of transport and the ease with which a CSS can be used have changed considerably in the mean time. In addition, neither of these studies considers an area of increasing importance on an EU and international

scale, that of the environmental impact of the CSS. These twin issues were therefore selected as an area worthy of further investigation.

2.5.2 Gaps in Ride Sharing Research

What emerged from the literature review of ride sharing was a real lack of meaningful modern research. each of the models created to date have a number of drawbacks principally related to their over simplification of the problem.

The assumption of uniform distribution (Tsao & Lin, 1999) leads to an under estimation of the number of matches while the assumption that individuals depart from the centroid of zones (Agatz et al., 2011) may lead to an over estimation of the number of matches. By directly examining origin and destination points Amey's (2011) study offers a more accurate calculation of the number of potential matches; however the techniques used are not scalable to larger populations. In contrast the techniques used by Šelmić, Macura, & Teodorović (2011) are scalable, but have not been applied to a real population. In summary, there is a need for work on ride-matching which uses real population data and tests assumptions with regard to the willingness of individuals to undergo inconvenience when identifying a match.

For understanding of ride sharing to be advanced, a better understanding of the number of potential matches is required. This requires, modelling techniques which are more closely based on real data, the use of techniques which are scalable to larger populations and a better understanding of which customer behaviours are important to increase the number of potential matches.

This gap in research, makes it fundamentally impossible to estimate the potential of ride sharing, both to offer a useful (economically viable) service to passengers and to produce measurable environmental impacts. The ride sharing models we develop in Chapter 6 are therefore focused on addressing this gap in the research so that in Chapter 7, the potential impacts of ridesharing can be calculated with some degree of confidence.

2.5.3 Gaps in Wellbeing and Transport Research

In reducing reliance on private vehicles, care must be taken to identify and mitigate any resulting negative impacts on social wellbeing. In understanding the links between wellbeing and travel patterns, little research has been done on general population travel patterns, wellbeing and the

use of private vehicles. While a number of studies have focused on the elderly (e.g. Ahern & Hine, 2011; Spinney et al., 2009) few have focused on general populations. Those studies which have focused on general populations have typically focused on one aspect of wellbeing (e.g. Smith, 2013). There is therefore a need for more general studies which evaluate the links between the use of and access to private vehicles and subjective wellbeing.

3 DATA AND DATA COLLECTION METHODS

3.1 Introduction

This chapter details the data and data collection methods used to calculate the economic & environmental impacts of changes to travel patterns, and to analyse the relationship between self-reported wellbeing and travel patterns. These analyses are described in Chapters 4, 5, 6 and 7.

Section 3.2 provides information about the data sources which were used in the course of the analyses. In particular these include the POWSCAR dataset, the Small Areas dataset from the 2011 Irish Census (CSO, 2012a, 2012b) and, databases which detail the Irish Car Fleet (Irish Tax and Customs, 2012a, 2012b). Section 3.3 then provides context for the research by summarising data published on transport in Dublin.

Section 3.4 describes a survey which was developed for this thesis to evaluate the sustainability of car sharers. The survey is also used to analyse the link between travel patterns and wellbeing within the Dublin region. Section 3.4 describes in detail the methodology used to develop the survey in three stages: preliminary design, development and distribution. The survey was used to gather information about the travel patterns of Irish residents. The chapter then concludes with a brief summary of the survey responses.

3.2 Data Sources

This section briefly describes the main data sources used in this work and summarises how they were used in the analyses described in Chapters 4, 5, 6 and 7.

3.2.1 Census 2011

A population census was conducted on all residents of the Republic of Ireland on Sunday 10th April 2011. The results of this census have been widely disseminated by the Central Statistics Office, Dublin Ireland. Two datasets produced from the results of this census have been used extensively throughout this research, namely the Small Area Population Statistics (SAPS) dataset (CSO, 2012b) and the POWSCAR dataset (CSO, 2012a).

The SAPS dataset provides a breakdown of the population of Ireland in 18,488 small geographic units, each of which is termed a "Small Area" (SA). Each SA has an average population of 248 and covers an average area of 3.8 km^2. Within Dublin, each of the 4,806 SAs, has an average population of 265 people and covers an average area of 0.19km^2. Across 15 themes, the SAPS dataset provides information about the number of persons and households within each SA who meet specific criteria. Of particular interest to the research were statistics about the number of cars per household, the work status of individuals, the age profile of each small area and the stage of the family cycle of households. In conjunction with the SAPS, the CSO provides a set of SA boundary files (CSO & Ordnance Survey Ireland, 2011) which are used to create the maps drawn in this and following chapters.

The POWSCAR dataset is available to researchers as part of the census 2011 processing programme. Geo-coded place of work & education data is provided for all workers and students from the age of 5 and upwards resident in Ireland on census night. A detailed file containing the demographic and socio-economic characteristics of these residents along with geo-coded home locations (SAs) was provided to the researcher for analysis in the course of this work.

Relevant portions of both the SAPS and POWSCAR datasets are summarised in Section 3.3. The SAPS dataset is used to carry out the geographic analyses described in Chapter 5 and the POWSCAR dataset is used to build the ride sharing model described in Chapter 6 and Chapter 7.

3.2.2 Irish Car Fleet Data

J. Bluett of the Department of Transport, Tourism and Sport, provided the researcher with a detailed breakdown of the Irish Car Fleet in 2010 (Personal Communication, 4th April 2012). For each Make/Model/Year/Engine Size combination, this breakdown detailed the number of cars registered in Ireland in 2010. For instance, in 2010, there were 4,547 Toyota Yaris 998c cars on the road which were registered in 2007. At the time the research was being carried out (July 2012), 2010 was the most recent year for which data was available.

To supplement this list, information from the Society of the Irish Motor Industry (SIMI) was used. The SIMI website (SIMI, 2012) provided detailed national vehicle registration statistics. This supplementary information provided a list of the number of new private cars sold each month in Ireland by make, up to the time period of the survey, i.e. March 2012. It did not however provide a breakdown of the specific models sold. This information was used to supplement survey

responses when estimating the costs of private vehicle ownership. A full description of how this information was used is provided in Section 4.2.

3.2.3 Vehicle Registration Tax, Open Market Selling Price Database

Upon importation into Ireland, private vehicles are assessed for an importation tax known as "Vehicle Registration Tax" (VRT). In order to assess this tax, and to enable those importing cars to estimate their liability, the Irish Tax and Customs service maintains an online valuation enquiry system, from which the "Open Market Selling Price" of new cars of a specific make, model and engine size can be estimated. (Irish Tax and Customs, 2012a). This database together with the depreciation curves, also supplied by the Irish Tax and Customs service (Irish Tax and Customs, 2012b) was used to supplement survey responses when estimating the costs of private vehicle ownership. A full description of how this information was used is provided in Section 4.2.

3.2.4 Survey

As part of this research a travel diary survey was developed and implemented to collect data on the travel patterns and travel spending of residents. The design and implementation of this survey is described in full in Section 3.4. The full survey is provided in Appendix A.

3.3 Transport in Dublin

The purpose of this section is to describe and summarise transport in Dublin, thus providing a background to the research work in later chapters. Following a brief sub-section introducing the city and population of Dublin, this section describes Dublin's transport infrastructure, i.e. the existing road and public transport networks. It concludes by describing the transport behaviour of Dublin residents.

3.3.1 Population and Demography of Dublin

Dublin County is located approximately half way along on the East coast of Ireland, of which it is the capital. Figure 3.1 illustrates the population densities across Dublin. The county has an area of 921km^2 and a population of 1,273,069 people (CSO, 2012f) spread across four administrative areas – (1) Fingal (2) Dublin City, (3) Dun Laoghaire-Rathdown, and (4) South Dublin. Table 3.1

provides a breakdown of the population of Dublin by Age, and Table 3.2 provides a breakdown of the population aged 15 and over, by principal economic status.

Table 3.1: Population of Dublin by Age Bracket, derived from Small Area Population Statistics (CSO, 2012b)

	Under 15	16-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	Total
Dublin City	85,075	24,168	109,817	98,672	67,294	53,581	40,974	30,226	17,805	527,612
South Dublin	64,583	13,382	41,149	46,408	34,479	29,639	20,948	10,292	4,325	265,205
Fingal	69,557	12,498	40,978	55,424	38,066	27,082	18,386	8,311	3,689	273,991
Dún Laoghaire-Rathdown	40,012	11,199	31,066	30,970	28,457	24,519	19,057	13,418	7,563	206,261
Total	259,227	61,247	223,010	231,474	168,296	134,821	99,365	62,247	33,382	1,273,069

Table 3.2: Population of Dublin, Aged 15 and Over, by Principal Status, derived from Small Area Population Statistics (CSO, 2012b)

	At Work	Looking For First Job	Unemployed having Lost or Given Up Previous Job	Student	Looking After Home/ Family	Retired	Unable To Work due to Sickness or Disability	Other	Total
Dublin City	227,429	5,086	46,613	56,377	31,594	58,475	19,242	2,767	447,583
South Dublin	106,534	2,361	23,678	22,307	19,212	20,611	8,802	419	203,924
Fingal	119,276	2,224	20,416	21,762	18,510	18,370	6,449	577	207,584
Dún Laoghaire-Rathdown	87,490	1,007	10,064	24,481	15,487	25,722	4,154	321	168,726
Total	540,729	10,678	100,771	124,927	84,803	123,178	38,647	4,084	1,028,817

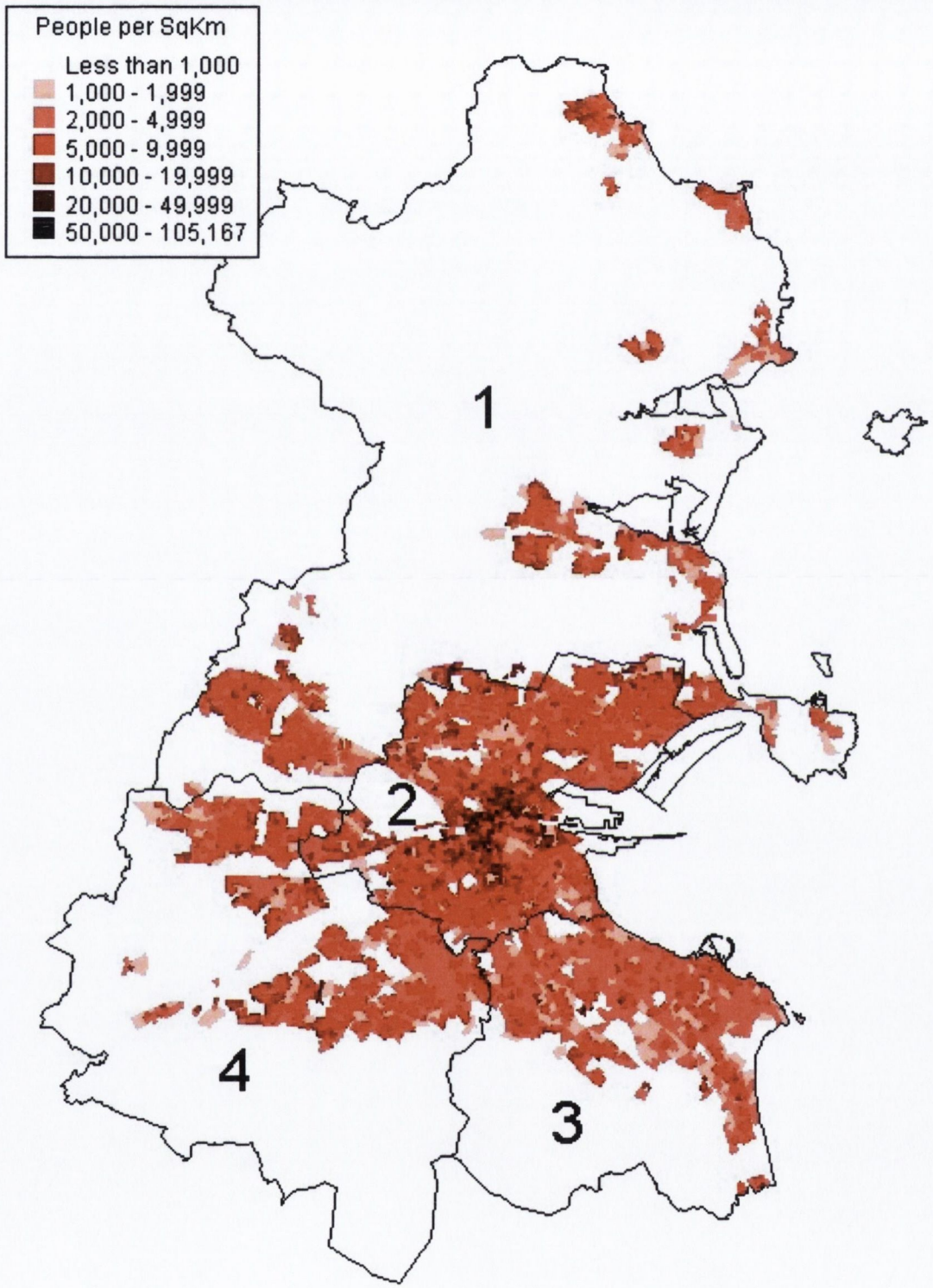

Figure 3.1: Population per Square Kilometre in Dublin, Derived from Small Area Population Statistics (CSO, 2012b)

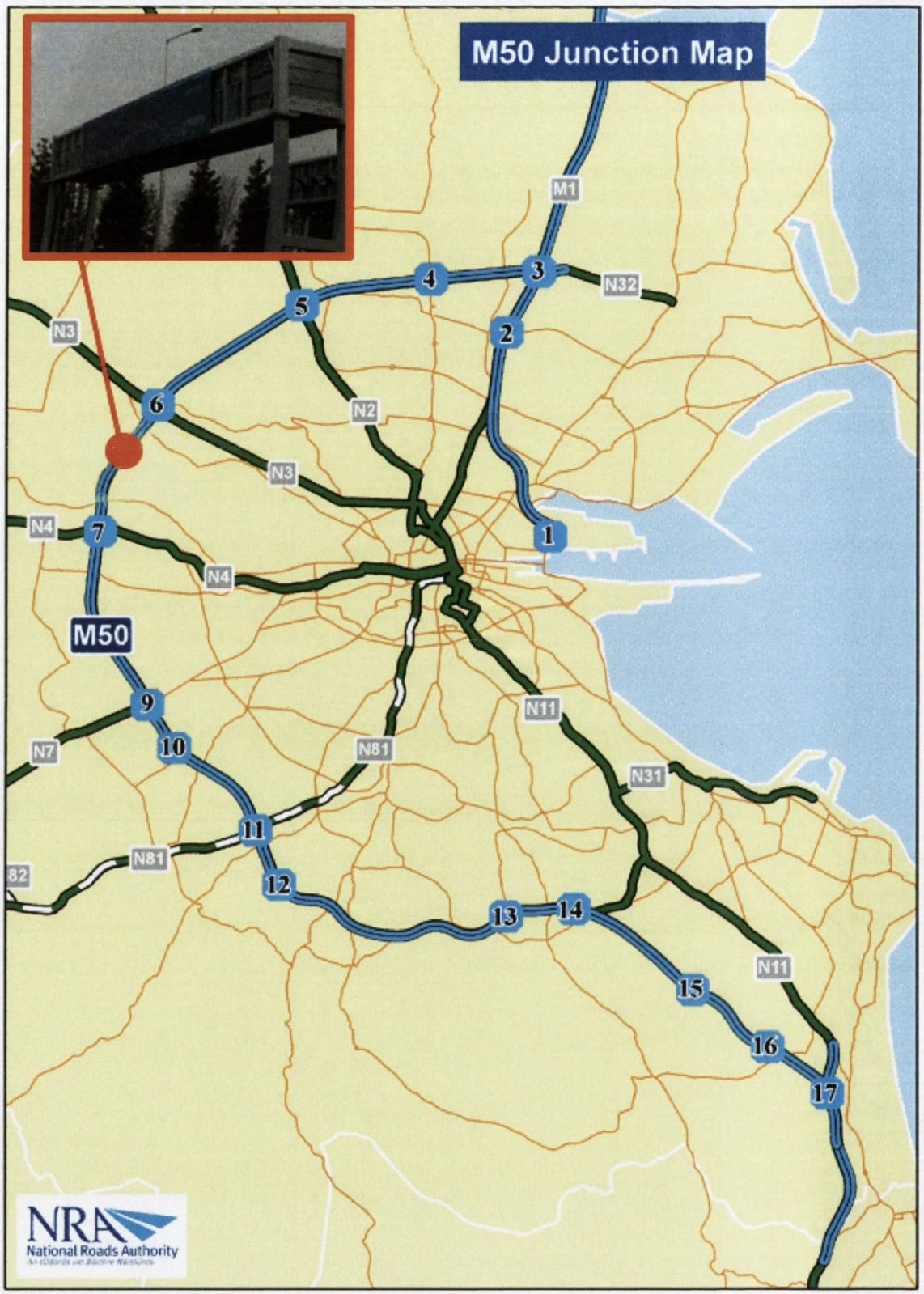

Figure 3.2: Dublin's Road Network, provided by the National Roads Authority and eFlow.ie (2013)

3.3.2 Road Network

Dublin city centre forms the hub of the Irish road network, and most major (national primary) routes radiate from it to the peripheral cities. These routes are numbered anti-clockwise from the M1 in the North (to Belfast) to the N11 in the South (to Wexford).

Dublin's urban core and most of its suburbs are surrounded by the M50 motorway, which forms a C-Shaped ring, allowing motorists to travel between the National Primary routes, while bypassing the city. Figure 3.2 provides an outline map of Dublin's road network.

3.3.3 Public Transport Network

Dublin has an extensive bus network and a limited rail network. Bus services are provided by Dublin Bus, which operates a fleet of 917 buses. In recent years, passenger numbers have fallen substantially, from almost 148 million in 2007 to 117 million in 2011. A re-organisation of the bus routes (the Network Direct Project), the introduction of the leap card for convenient payment and through the introduction of real time information systems this fall in passenger numbers has been stabilised, and in 2012 passenger numbers were 115.2million (Dublin Bus, 2012).

Figure 3.3 illustrates the routes operated by Dublin Bus in 2012. As is shown, bus routes provide services to the areas of the city with higher residential densities. Routes connecting the suburbs to the city centre tend to be relatively direct, while those that connect suburbs tend to be circuitous.

The Dublin rail network is fragmented and serves a limited number of city areas. Three options are available: Luas services, Dublin Area Rapid Transit (DART) services and Arrow Services. A map showing stops on the DART and Arrow Service network is given in Figure 3.4. Veolia Transdev operates Luas, which provides tram services on two unconnected lines – the red line, and the green line. The red line, is 20km in length and runs to the South and West of the city, connecting the suburb of Tallaght to the city centre. It also serves as a connection service between two main rail stations (Connolly and Heuston), and to national bus services which operate from Busáras. The green line is 16.5km in length and runs to the South of the city, connecting Sandyford and Brides Glen to St. Stephens Green in the city centre. In 2012, the two lines together carried 29.4 million passengers, a daily average of 80,000 (Luas.ie, 2013)

Figure 3.3: Map of Bus Routes Operated by Dublin Bus in 2012, derived from data provided by Dublinked.ie (2013)

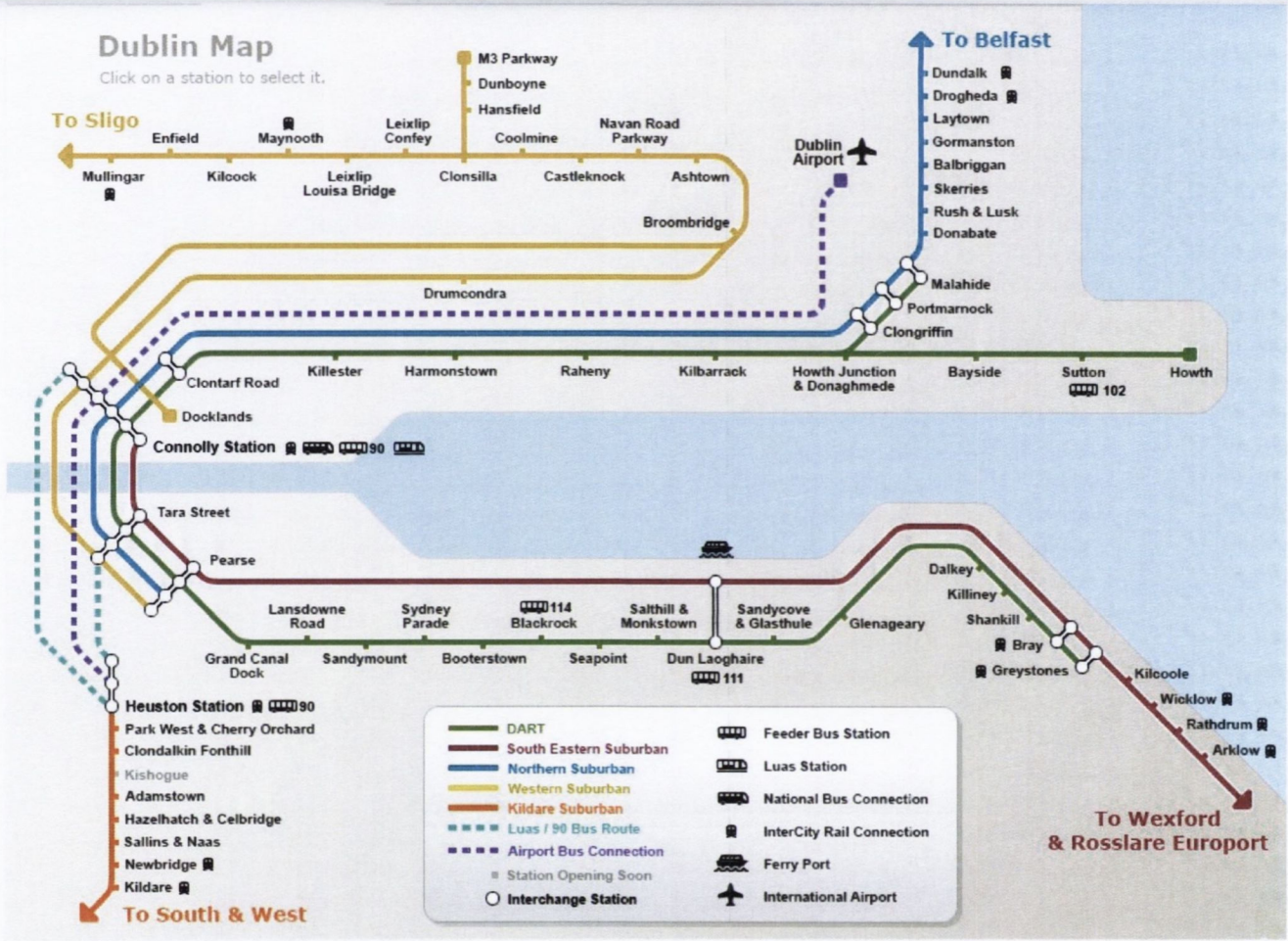

Figure 3.4: Map of Dublin Train Stations (Irish Rail, n.d.)

Heavy rail services comprise the DART and Commuter services, both of which are operated by Irish Rail. Commuter Services are operated on four lines Northern, South Eastern, South Western and Western, extending to Dundalk, Gorey, Portlaoise and Longford respectively. The DART is an electrified line which follows the coastline from Malahide in the North to Greystones in the South. The DART's route is overlapped with the commuter service lines, using the same track as the Northern and South Eastern Commuter services. The Irish Rail annual report (Irish Rail, 2012) does not provide a breakdown of passenger numbers on these services, however figures from the POWSCAR dataset (CSO, 2012a) show that for 41,845 adult commuters within Dublin indicated that rail services were their primary means of travel to work.

3.3.4 Travel Patterns in Dublin

This section provides tables and figures derived from the Small Area Population Statistics (SAPS) and POWSCAR (CSO, 2012a, 2012b) datasets described in Section 3.2.1 to describe travel patterns in Dublin. This description is given to provide background to the work carried out in Chapters 4, 5, 6 and 7 and to enable comparisons to be made between the figures derived in the course of this work and figures from other sources.

The two datasets are supplemented by the results of the National Travel Survey 2009 (CSO, 2011b), the Household Budget Survey 2009 – 2010 (CSO, 2012e) and the Irish Bulletin of Vehicle Driver Statistics (Department of Transport Tourism and Sport, 2011).

All Travel

The most recent National Travel Survey (NTS) (CSO, 2011b) presents information about travel in Dublin and Ireland. Dubliners made an average of 18 journeys per week, spending an average of 446 minutes travelling and covering an average distance of 151km. While Dubliners averaged 1 more journey and 59 more minutes travelling than the rest of the Irish population, they travelled 97 fewer kilometres.

Some of this difference can be attributed to the difference in modal split between Dublin and the rest of the country. The NTS (CSO, 2011b) also found that 54% of trips in Dublin are undertaken in a private car by drivers, with a further 7% of trips being undertaken in a private car by passengers. The proportion of journeys made by car is lower for those under the age of 25 and over the age of 55, peaking in the 45 to 54 age brackets. Walking accounts for 21% of journeys, with bus and rail travel together account for 13% of journeys. The remaining modes, Van/Lorry/Other and cycling

account for the remaining 4% and 2% respectively. Outside Dublin car travel accounts for a total of 78% of journeys, and Van/Lorry/Other travel for an additional 5%. The remaining modes carry a significantly smaller proportion of journeys than in Dublin, with cycling and rail accounting for 1% each, bus travel for 2% and walking for 15%.

Commuter Travel

The NTS (CSO, 2011b) found that work accounts for 25% of all journeys in urban areas. Education accounts for a further 3% of journeys. Table 3.3 presents the number of adults in Dublin using each mode of transport on their morning journey to work or college. A further 756 second level pupils report driving themselves to school, and 70,961 primary and second level pupils report travelling to school as passengers in private cars. With 218,592 adults reporting driving to work and a total of 86,867 children and adults reporting travel as passengers, it is clear that commuting in a single occupancy vehicle accounts for at least 28% of regular morning commuter journeys in Dublin. Figure 3.5 provides a geographical illustration of the data presented in Table 3.3, highlighting regional differences in the modal split.

Table 3.3: Adults Travelling to Work or College around Dublin, derived from the POWSCAR database, (CSO, 2012a)

	Dublin City	South Dublin	Fingal	Dun Laoghaire-Rathdown	County Dublin (Total)	
On Foot	51108	6224	6509	8036	71877	15.4%
Bicycle	17823	3375	2240	4762	28200	6.0%
Bus, Minibus or Coach	39227	14604	12467	8983	75281	16.1%
Train, DART or Luas	14684	2641	12154	12366	41845	9.0%
Motorcycle or Scooter	1676	1069	884	815	4444	1.0%
Private Car (as Driver)	65837	54871	57923	39961	218592	46.9%
Private Car (as Passenger)	5415	3961	4192	2338	15906	3.4%
Van	2189	2287	1992	836	7304	1.6%
Other, including lorry	161	106	154	44	465	0.1%
Work mainly at home	95	21	29	38	183	0.0%
Not Stated	1063	499	497	369	2428	0.5%
Total Population	199278	89658	99041	78548	466525	100.0%

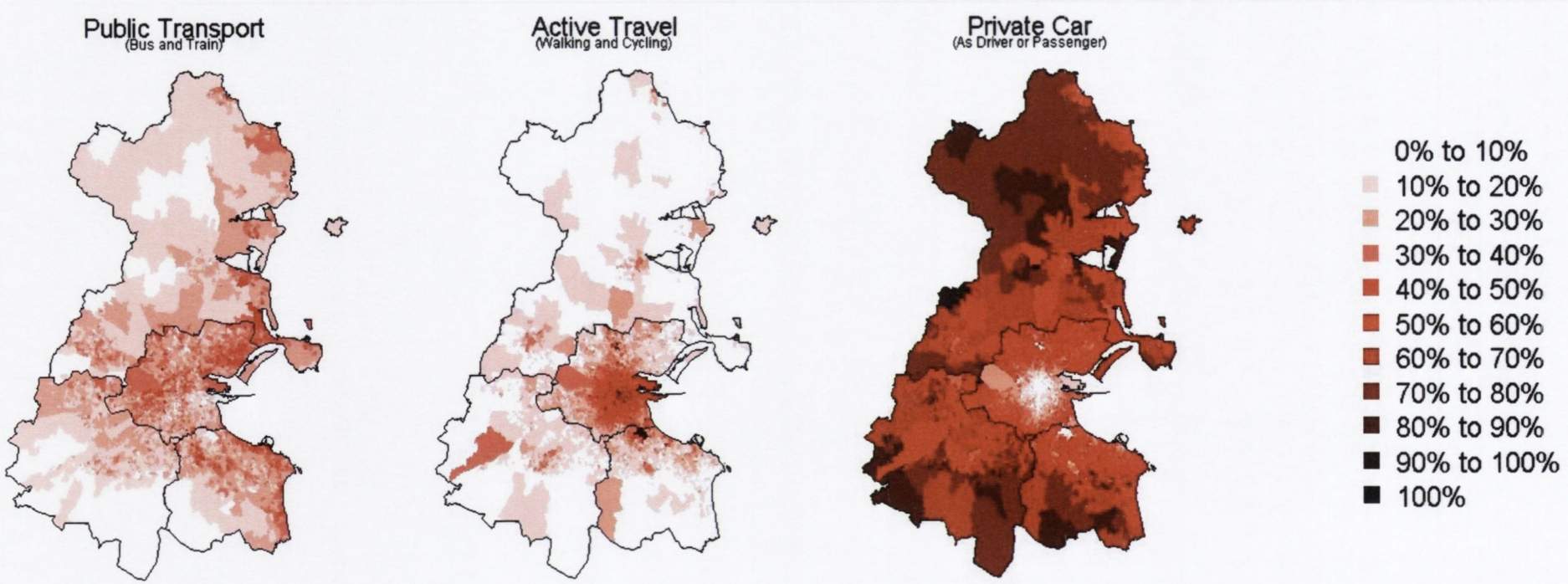

Figure 3.5: Proportion of Adults Travelling to Work or College Using Each Mode of Transport, Dublin, derived from the POWSCAR database (CSO, 2012a)

3.3.5 Car Ownership and Licensing Levels

The Irish Bulletin of Vehicle Driver Statistics (Department of Transport Tourism and Sport, 2011) indicates that in 2011, there were 1,887,810 private cars registered in Ireland. While this number has remained relatively stable since 2007, it represents a 36% increase over the 2001 figure and a 126% increase over the 1991 figure. This has resulted in severe congestion in urban and suburban areas around Ireland, in particular in Dublin.

Table 3.4: Household Car Ownership Levels around Dublin, derived from the Small Area Population Statistics database (CSO, 2012b)

	Number of Households with __ Cars					
	None	One	Two	Three	Four or More	Total
Dublin City	79,300	85,069	36,255	5,781	1,442	207,847
South Dublin	13,007	38,912	30,980	5,440	1,538	89,877
Fingal	11,338	40,326	34,493	5,365	1,429	92,951
Dun Laoghaire-Rathdown	10,583	31,457	27,252	5,128	1,366	75,786
Total	114,228	195,764	128,980	21,714	5,775	466,461

Table 3.4 summarises the car ownership levels of households in Dublin. 75% of households have one or more cars, and allowing four cars in each household with *"four or more cars"*, 541,966 cars are owned by residents of Dublin. As the number of cars exceeds those driving to work by a considerable margin, this suggests that many households find car ownership desirable and/or necessary even without a requirement to drive to work.

Licensing levels are also high in Ireland. The Irish Bulletin of Vehicle Driver Statistics (Department of Transport Tourism and Sport, 2011) found that there are 2,666,559 licensed Irish Drivers of which 271,428 have a provision license. That is 72% of the adult population of Ireland have a full licence, with a further 8% possessing a provisional licence. In Dublin a lower proportion of the adult population are licensed drivers. The bulletin (Department of Transport Tourism and Sport, 2011) finds that 671,157 adults in Dublin are licensed drivers of which 80,390 hold a provisional licence. That is 62% of the adult population of Dublin have a full licence, with a further 8% possessing a provisional license.

3.3.6 Spending on Transport

The Household Budget Survey 2009 – 2010 (CSO, 2012e) provides a breakdown of weekly household spending on transport in Dublin. Average spending on transport was found to be €114.30 per week, with an average household having 1.82 adults over 20, 0.24 person aged 16-20 and 0.58 children aged 15 and under. Allowing an average of 1.95 adults over 18 per household, annual spending on travel per adult is €3,047.75. Weekly household spending on transport comprises 10.8% of the average Dublin household disposable income of €1,054.88.

77.4% (€88.44) of this budget is spent on car ownership, travel and the associated costs, with the largest portions of this spending being on car purchase costs (€30.98), fuel costs (€27.76), and insurance (€11.51). Average spending on public transport amounted to €9.98. Spending on bicycles totalled €1.00, however this figure also includes bicycles purchased for children and for leisure cycling and may not indicate the cost of cycling for transport. The majority of the remaining transport spending is comprised of international air travel and taxis.

3.4 Survey

This section describes the process used to design and implement the survey. The first sub-section describes the preliminary design phase. The following sub-section discusses each part of the survey in detail. The final part of this section describes the administration of the survey, i.e. the piloting and distribution process.

3.4.1 Preliminary Survey Design

Prior to the design of the survey, a number of decisions were made which guided the questions selected for inclusion and subsequently the wording of those questions. In particular this preliminary design stage defined the survey's objectives, identified suitable source surveys, identified appropriate indicators related to the three pillars of sustainability, specified appropriate limits to the survey, and selected the appropriate survey software. Each of these decisions is discussed in more detail below.

Objectives of the Survey

As originally conceived, the scope of this study was to evaluate how membership of a Car Sharing Service (CSS) changes an individual's transport sustainability as measured by economic, social and

environmental components of their travel patterns. The purpose of the survey was to enable the researcher to assess respondents' travel patterns and relate these to a selection of economic, social and environmental indicators, and thereby evaluate the sustainability of travel patterns before and after joining a CSS. The intended purpose of the survey and how the results from it were applied differ due to the profiles of those who responded, in particular the lack of CSS users. These issues are further discussed in Section 3.5.

Based on this original scope, a structured revealed preference questionnaire was developed and implemented. This was intended to survey members of the existing Irish CSS, those interested in joining the CSS and the wider public.

Existing Literature

During the preliminary design phase, similar surveys carried out by other research organisations were identified and used to inform the development of the survey. A key influence on the development of the questionnaire was the survey carried out by Martin and Shaheen (2010) in their work on car sharing. They surveyed several thousand members of car sharing services across North America, asking respondents to report their household's travel behaviour in the period before they joined car sharing and at the current time. This study was used to inform the structure of the survey, particularly the separation of questions related to private vehicles and public transport. The Martin and Shaheen (2010) survey began by asking for details of car journeys, i.e. make, model, year, commuting behaviour and annual mileage of cars driven prior to joining car sharing and currently. Subsequently it asks for details of hours spent and round trips per week made before and after joining car sharing using rail, bus, walking, bicycling, carpool, taxi, rental cars and ferries as modes of transport. The next section contained a series of questions on how behaviour would change in the absence of car sharing. The survey concludes by ascertaining socio-demographic information including gender, education levels, age group, income levels and zip codes.

In general the questions were clearly phrased and the answer selections were comprehensive, however due to the complex nature of the information being sought, certain questions contained lengthy descriptions. For instance, when asking respondents to calculate annual mileage the following description was provided:

> *"Everyone has different driving habits, but most people can break down driving needs into two trip types, (1) driving to work (for those who commute by car), and (2) driving everywhere else. To help you with computing annual miles, start with the round trip*

distance a vehicle is driven during a typical work day, then multiply that by the number of days per week the vehicle is taken to work (usually 3 to 5). Now you have commuting miles per week. You can multiply that by the number of weeks per year that you go to work at that location. Non-work miles are much more variable over a year. These are the miles driven around town for errands as well as out of town trips over the CURRENT year. Add this non-work estimate to the commuting miles. The sum is your total annual miles for that vehicle."

Martin and Shaheen (2010)

In the development of the survey for this project, considerable effort was made to avoid such lengthy descriptions and thus ease the response burden.

A second source of reference material during preliminary design was the series of car sharing surveys carried out by the EU funded *momo* project. These surveys and their results are described by Loose (2010). As these were less comprehensive than the survey conducted by Martin and Shaheen (2010), this source was used confirm that the final survey was comprehensive and to identify potential areas for comparison with other research.

Neither the Martin and Shaheen (2010) nor the *momo* surveys requested information related to social sustainability or the costs incurred in travel, therefore different sources were used to identify suitable questions for these issues. For questions related to the cost of transport, the Household Budget Survey 2004/2005 (CSO, 2007) was a key reference. Other sources directly relevant to Ireland were also consulted. Of these, the most important was the 2011 Irish Census (CSO, 2011f). This contains several socio-demographic questions and a question relevant to health and wellbeing which was included as an indicator of social sustainability.

Indicators of Sustainability

As discussed in Section 1.4, sustainability has three principal components – environmental, economic and social. Appropriate indicators were therefore selected for each of the three components. The range of possible indicators, the indicators selected and the reasons for their selection are now discussed.

A variety of environmental indicators have been used in research. These include energy flow indicators, ecological footprint calculations, material flow indicators and greenhouse gas emissions estimates. Carbon dioxide emissions have been established as an environmental indicator in a large volume of research work related to sustainability, transport and car sharing (e.g. Chan, 2009; Firnkorn & Müller, 2011; Glaeser & Kahn, 2010; Martin & Shaheen., 2010).In

contrast to other potential indicators such as ecological footprint, excellent data is available in key areas such as personal emissions, population emissions and vehicle emissions (e.g. EPSSU, 2009, 2012; Irish Tax and Customs, 2012a; Kenny & Gray, 2009). In addition, the largest previous report on the environmental impacts of car sharing uses carbon dioxide as its keystone indicator (Martin & Shaheen, 2010). For these reasons, changes in an individual's CO_2 emissions were selected as the principal environmental indicator. The behaviour change upon joining a CSS may affect all aspects of an individual's travel pattern, therefore the CO_2 emissions impact of an individual joining a CSS can only be examined as a part of their overall personal transport emissions. As a result the survey is designed to fully assess a respondent's CO_2 emissions from travel.

The second pillar of sustainability is the economic pillar. Two potential indicators were identified, cost and time. Cost is the most commonly used economic metric. On an individual level this may be household income or the cost of acquiring a particular product or using a particular service. As with the environmental impacts of joining car sharing, the economic impact on an individual can only be examined as a part of the overall personal transport budget. The survey therefore could not focus only on the costs of CSS membership but needed to fully assess each respondents transport budget. The second indicator, time, was also included as time has both an economic and social value. Time is a cost to the individual which could potentially be applied to more productive pursuits, such as employment or education (Stutzer & Frey, 2008).

The impact of joining a CSS on the social remit is more nebulous than the economic and environmental impacts. The social component of sustainability was therefore the most difficult of the three areas in which to identify appropriate indicators. The links between transport and social sustainability were explored more fully in Section 1.5 and Section 2.4. As a result of the literature review described in Section 2.4, two wellbeing indicators were selected for this survey. The WHO-5 wellbeing score (Bech, Olsen, Kjoller & Rasmussen., 2003) and Question 18 from Irish Census 2011 which asked "How is your health in general?" (CSO, 2011f).

The identification of the indicators and limitations enabled the clear formulation of specific hypotheses to be tested using the survey responses. Four hypotheses were selected, each relating to at least one of the three pillars of sustainability (economic, environmental or social)

1. On average users of car sharing schemes reduce their transport carbon footprint in the first year after joining.
2. On average users of car sharing schemes reduce their transport costs in the first year after joining.

3. On average users of car sharing schemes reduce their transport time costs in the first year after joining.
4. On average users of car sharing schemes increase their sense of wellbeing in the first year after joining.
    i. On average users of car sharing schemes increase their score on the WHO-5 wellbeing index in the first year after joining.
    ii. On average users of car sharing schemes improve their self-rated health in the first year after joining.

Constraints of the Survey

With the indicators in mind, a number of constraints to the data-collection process were established in order to ensure consistent results were obtained and to reduce the response burden. In particular the study was limited to Ireland, and personal travel.

Respondents were asked to only include travel which took place within Ireland and emissions calculations were limited to Ireland. Emissions calculations focus on achievable reductions to Ireland's CO_2 emissions under the Kyoto protocol, therefore emissions generated outside this boundary both by individuals travelling abroad and from the manufacturing process of vehicles were excluded. Further to this CO_2 emissions from public transport differ by country as a function of the type of vehicle being used by companies and local passenger usage numbers. The range and emissions profile of private vehicles also varies considerably between countries. Public transport and private vehicle usage abroad therefore had a large potential to introduce inaccuracies to the analysis.

Respondents were also asked to limit their responses to personal travel, i.e. respondents were asked to exclude required business travel from their travel diary reports, and were not asked to provide travel details for other members of their household. To date much of the research on car sharing has focused on household travel patterns rather than personal travel patterns. Both the Martin and Shaheen (2010) survey and the surveys described by Loose (2010) focus either wholly or partially on household travel patterns. In the wider research on travel patterns both approaches are common. Loose (2010) found that on average 1.1 people used each car sharing account, i.e. fewer than 10% of car sharing accounts were shared. In informal trials of pre-pilot surveys it was found that focusing on the individual reduced response burden and generated more consistent responses. Framing questions based on personal transport was simpler and by focusing exclusively on the individual the volume of information required from each respondent

was greatly reduced, the survey was more readily understood and the survey was more quickly answered.

Survey Software

The survey was designed and carried out using LimeSurvey software (Schmitz, 2012). LimeSurvey was chosen for the unlimited numbers of responses it allows, the wide selection of question types and the flexibility with regard to presentation styles. In particular LimeSurvey facilitated the question about a respondent's home location, i.e. it presented a map of the Dublin area and asked users to identify their home locations. The LimeSurvey software also allowed the researcher to host the survey on a dedicated website with a recognisable and memorable website address.

3.4.2 Detailed Survey Design

From the preliminary design stage, the survey design process progressed to the detailed design stage. Key elements of this process are discussed in this part of the survey section, and the full survey is provided in Appendix A. From the four hypotheses being tested, it was possible to identify the principle areas which the survey must cover. In wording and structuring the questionnaire, a number of decisions were taken and a number of areas posed challenges. These are discussed in detail below.

The survey involved framing questions in such a way that whatever their travel patterns, respondents could give meaningful and accurate answers. To avoid ambiguity, the answers were either multiple choice or allowed only numeric answers. Due to the length and complexity of the survey, funnelling and repetition were used extensively to allow respondents to progress rapidly through the survey. A progress bar also enabled respondents to gauge their progress. The survey structure is now discussed in five sections – introductory, non-private vehicle modes, private vehicles, socio-demographic questions and concluding remarks.

Introductory Section

The introductory prompts gave a brief outline of the structure of the survey and its purpose. It introduced the structure of the survey by providing the following brief description:

- The first section covers your travel on public transport, walking and cycling,
- The second section covers your travel in private cars and other private vehicles,

- The third section covers some personal and quality of life details.

The introductory section also provided contact details for the researcher and details of the competition which was run to encourage members of the public to respond to the survey. The competition was open for six weeks, closing on March 15th 2012 and had four prizes. These were two general prizes of €250 and €100 "one4all" shopping vouchers and two prizes open to members of GoCar, the Irish CSS, of GoCar vouchers worth €100 and €50.

As both kilometres and miles are commonly used in Ireland, the decision was made to give respondents the option of using miles or kilometres throughout the survey. Respondents were also prompted to refer to internet mapping software to assist with distance estimation while completing the survey.

Non-Private Vehicle Modes

The second part of the survey covered travel in modes other than private vehicles. The list of modes included in the non-private vehicle modes section was based on the list provided in the survey carried out by Martin and Shaheen (2010) and the list of possible modes of transport to work provided by the Irish 2011 Census (CSO, 2011f). The final set used was Bus (including Dublin Bus, Bus Éireann, CityLink Coaches), Train (including Luas, DART, Intercity Rail and Arrow services), Cycling, Walking, Taxi and CSS vehicles.

Each question set in the non-private vehicle modes repeated the previous questions, with a simple icon used to reinforce which mode of transport was under consideration. Figure 3.6 illustrates the main question set used. This asked the number of journeys made, the time spent (in minutes) and the distance travelled on the mode.

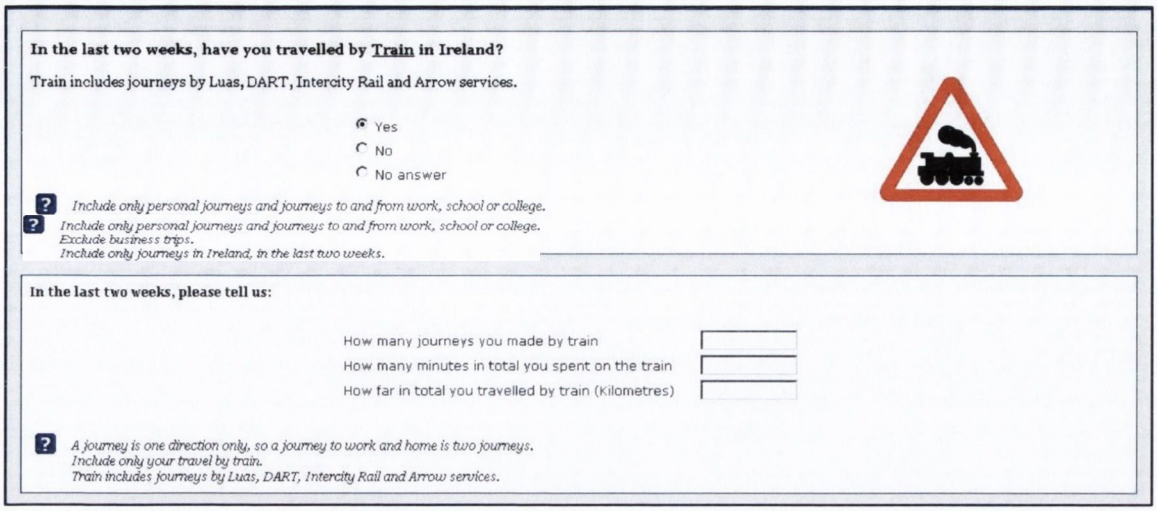

Figure 3.6: Sample Survey Questions - Train

Questions on the cost of travel by public transport were also included in this section. Public transport costs may be incurred on an annual basis through the use of annual tickets, or over a variety of shorter time periods from monthly tickets, to weekly tickets to daily tickets. At the time of the survey, ticketing in the Irish transport system was complex. In addition to single and return tickets, annual, monthly and weekly tickets were available which a respondent may have purchased outside the two week travel diary period. Further complicating factors included multi-journey tickets, combined rail and bus tickets, cash fares and the availability of "tax saver" annual tickets. The solution implemented is described below.

When respondents answered yes to travelling by bus or train, they were asked about their combined bus and train ticket costs in a section which immediately followed the questions on bus and train journeys. They were offered a selection of ten ticket types and asked to tick all that applied to their travel in the previous two weeks. The ticket types offered were: a) Free Travel Pass, b) Annual Ticket(s), c) Annual Ticket(s) (Tax Saver), d) Monthly Ticket(s), e) 30 Day Ticket(s), f) Weekly Ticket(s), g) Ten Journey Ticket(s), h) Five Day and Three Day Ticket(s), i) One Day Ticket(s), j) Smart Card, Cash Fares, Single and Return Ticket(s).

Those who indicated they had not made any journeys by bus or train were asked whether they currently had any of the following: a) Free Public Transport Pass b) Annual Ticket for Bus/Luas/Train c) Annual Tax Saver Ticket for Bus/Luas/Train d) Monthly Ticket for Bus/Luas/Train, e) 30 Day Ticket for Bus/Luas/Train and k) None of these.

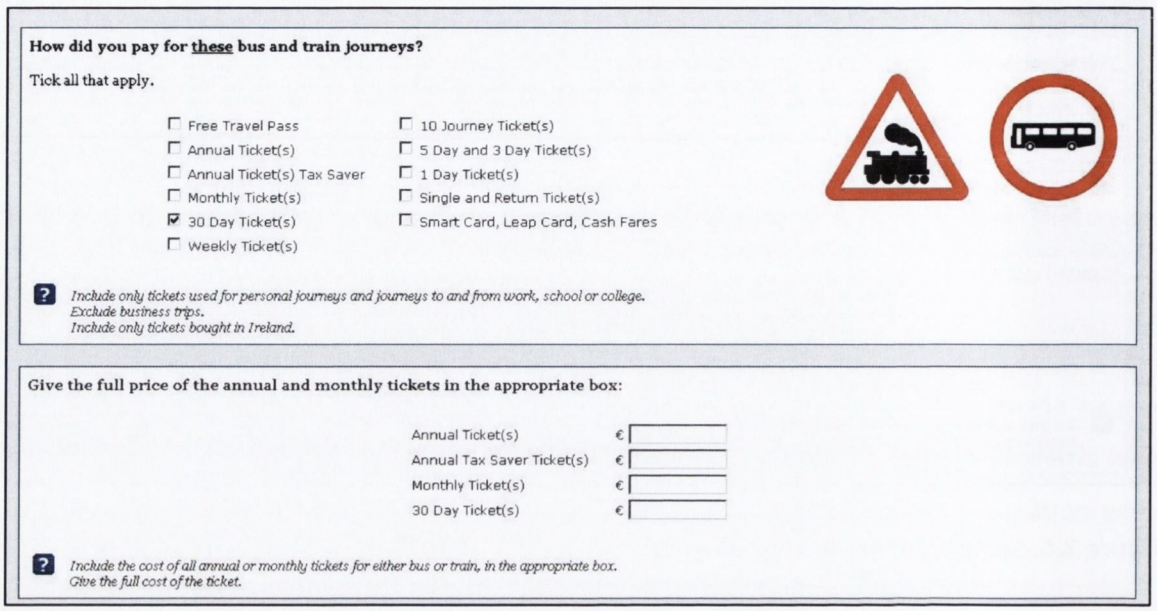

Figure 3.7: Survey Questions – Cost of Travel on Public Transport

Where respondents indicated one or more of items (b – e) applied, a follow up question asked the respondent to list individually, the full price of tickets by category. Where respondents indicated item f) applied, a follow up question on weekly tickets was presented. This asked "In the last two weeks, how much did you spend on 7 Day tickets?" Where respondents indicated item g) applied, a two question set was presented. This asked first "In the last two weeks how many journeys did you use the ten journey ticket for?" and second how much the specific ten journey ticket cost. Finally respondents who indicated one or more of items h-j) applied were asked "In the last two weeks, how much did you spend on other travel tickets, e.g. five day tickets, three day tickets, one day tickets, single tickets, return tickets, cash fares, smart card fares. Figure 3.7 illustrates the initial filter question, and the question presented to respondents who had used a 30day ticket.

Private Vehicles

Travel in private vehicles can include travel in cars, vans or motorcycles. As with the previous section, questions in this section needed to ascertain two key areas of travel behaviour – the respondent's volume of travel (number of journeys, distance, and time) and the respondent's cost of travel. To reduce response burden, questions in the section of private vehicles, as closely as possible, mirrored those asked in the previous section on non-private vehicle modes. However the order of the questions was somewhat reversed, in that this section first asked about vehicle ownership and ownership costs and subsequently about travel behaviour.

Private vehicle costs can be divided into three components: a) ownership costs, b) annual expenses and c) day to day running costs. With this in mind the survey was designed to find out what vehicles, if any, respondent's owned, what vehicles, if any, they had contributed to the maintenance of, and what they had contributed to vehicle running costs in the previous two weeks. These were separated in the survey, with ownership costs and annual expenses addressed separately to day to day running costs.

The first question in this section was a filter question, which asked "except for fuel, have you contributed to the cost of a private vehicle in the last 12 months?" Four answer options were given and respondents were asked to choose one: a) yes to vehicle(s) I owned, b) yes to vehicle(s) owned by others, c) yes to several vehicle(s) owned by myself and others, and d) no.

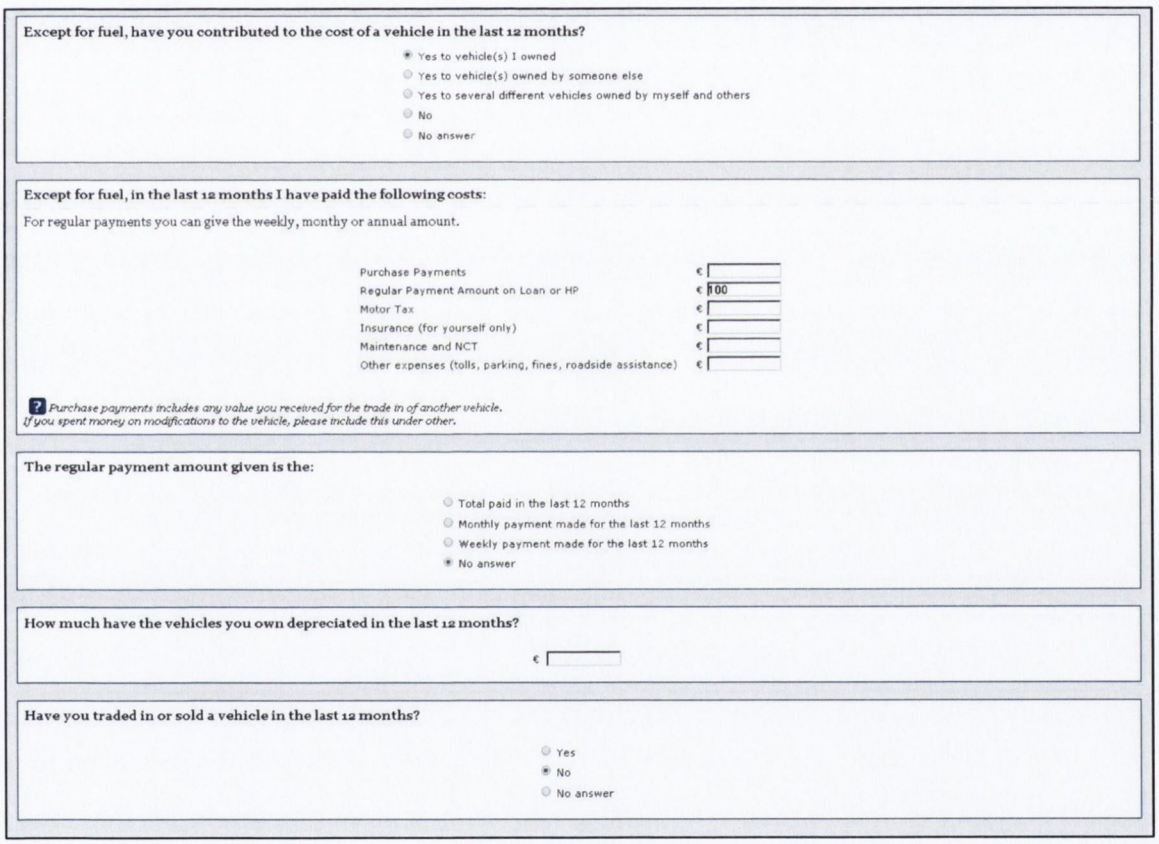

Figure 3.8: Sample Survey Questions – Contributions to Costs of Private Vehicles

Where respondents indicated they had contributed to the cost of a vehicle, they were then asked to provide details of the following payments in the last 12 months: Purchase Payments, Regular Payment Amount on Loan or HP, Motor Tax, Insurance (for yourself only), Maintenance and National Car Test (NCT), and Other expenses (tolls, parking, fines, roadside assistance). For the

question on "Regular payments" respondents were offered an option to provide the regular payment per week, per month or the total of payments made in the last year. Where respondents indicated they owned one or more vehicles, they were asked how much it had depreciated and also whether they had traded or sold a vehicle in the last 12 months, and if so how much they received. This question set is illustrated in Figure 3.8.

The second set of questions on private vehicles dealt with the type of private vehicle used, the volume of travel undertaken, and the day to day running costs of travel in those vehicles. An initial filter question was again used to enable appropriate questions to be presented to the respondent. The filter question asked "In the last two weeks have you travelled in a private vehicle?" and presented five answer options: a) Yes one vehicle, b) Yes two vehicles, c) Yes more than two vehicles, d) I own a vehicle but have not travelled in any private vehicle for longer than two weeks and e) No.

Where respondents chose option a), they were asked about travel in that vehicle, where respondents chose option b) they were asked about travel in both vehicles, where respondents chose option c) they were asked about travel in the vehicle in which they travelled the furthest distance and then about travel in other vehicles together, where respondents chose option d) they were asked for details of that vehicle related to its CO_2 emissions level, and where respondents chose option e) they were prompted to continue with the next question set.

To enable the calculation of CO_2 emissions, details of the private vehicle were ascertained. The Martin and Shaheen (2010) survey asked respondents for details of the make, model and year of registration of cars driven, however during the pilot phase of the survey, it was found that this information did not allow for adequate comparison with the databases of vehicle CO_2 emissions available. As of June 2008 Irish motor tax has been related to the CO_2 emissions rating of the vehicle. Prior to this, vehicles were taxed based on their engine size, which is also related to the engines CO_2 ratings. The decision was therefore taken to request details of the year of manufacture and tax band (post July 2008) or engine size (pre July 2008) of each car and use this information to interpolate CO_2 emissions for each vehicle in which journeys were made.

The questions regarding a respondent's volume of travel were phrased and structured in the same way as those used in the non-private vehicle modes section. However two changes were made. The question on the number of journeys made was divided into two, and respondents were asked to distinguish between journeys made as a driver and journeys made as a passenger.

In addition, respondents were asked "On average how many people accompanied you in this vehicle?"

In the final part of this sub-section the remaining travel costs, i.e. day to day running costs were ascertained. Immediately after enumerating the number of journeys they had taken, respondents were asked how much they had spent on fuel in the previous two weeks and how much of their spending on vehicles (in the previous two weeks) they could claim back from other sources, e.g. their employer. Together this series of questions enabled the calculation of the cost of travel in private vehicles and the CO_2 emissions created by that travel as described in Section 4.2 and Section 4.3.

Socio Demographic Questions

In line with the advice presented in Conducting Online Surveys (Sue & Ritter, 2007), the most personal, socio-demographic questions were placed at the end of the survey. The socio-demographic questions allowed responses to be segmented for further analysis. Also included in this section were the questions related to social sustainability, i.e. the WHO-5 wellbeing survey and the question on health.

The two questions which directly measure wellbeing were identified at the preliminary design stage and included as is. The socio-demographic questions were based on Census 2011 questions (CSO, 2011f) as far as possible. This allowed for easy comparison of results with the general population. A number of options for these questions were considered, and weighed against the need to reduce the length of the survey. In the final survey, sex, age and household composition, residence and principal status with regards to work were included.

Concluding Section

A concluding section thanked respondents, offered respondents a chance to comment on the survey, assist in distributing the survey through social media, and to enter the competition by providing an email address.

3.4.3 Survey Administration

This section briefly describes the survey piloting and distribution process. Twenty respondents were asked to answer a prototype of the survey. Based on their responses and comments, a number of changes were made. These are summarised below.

Piloting Process

In the pilot survey, respondents found certain questions complicated and not easily understood. One particular complaint was the switching between different time periods, with years and months being mentioned directly in each question and other time periods being mentioned in the socio-demographic portion of the survey. They also found the response burden high, stating that the survey was too long and expressing difficulties of recall.

At the pilot survey stage, the questions about journeys were divided into journeys to work and other journeys. Following feedback, this division was removed. Respondents were also asked about "their average travel per month over the past year". This wording was based on the Martin and Shaheen (2010) wording which asked respondents for their annual mileage. The question on wellbeing adopts a two week time frame. A two week time frame allows respondents to more accurately recall their actual travel behaviour. Respondents are therefore asked to give the total number of journeys, total time taken and total distance travelled on each mode of transport in the last two weeks.

Respondents to the pilot survey also indicated that they were wary of answering questions on their health and wellbeing and unsure how it related to the overall aims of the survey. An explanatory note was therefore added both in the introductory prompts and immediately prior to the wellbeing section.

Online Distribution

The use of internet surveys has been criticised due to the bias it can introduce as not all members of the population have internet access. However Dublin is a region with a high level of internet penetration. Of the households which answered the question on internet access in the 2011 Census, (CSO, 2012b) 74.8% of Dublin households reported having broadband access and 80.1% of households reported having internet access. A breakdown of the numbers by administrative area and internet type is provided in Table 3.5.

Furthermore, members of a CSS require internet access to make and change reservations. GoCar's primary method of communication with its members is via the internet. The main target audience of the survey is therefore those with internet access. Previous similar research into Car Sharing, (e.g. Martin & Shaheen, 2010) has also been conducted online. Finally, due to the use of funnelling techniques used to reduce response burden, the only feasible way of conducting the survey was via computer, making an online survey the most viable option.

Table 3.5: Household Internet Access around Dublin, derived from the Small Area Population Statistics Database (CSO, 2012b)

County	Broadband	Other Internet	No Internet	Total Households	% Households w/Internet Access
Dublin City	137669	11763	51454	200886	74.4%
South Dublin	68306	4186	15455	87947	82.4%
Fingal	73868	4820	12242	90930	86.5%
Dun Laoghaire Rathdown	59750	3313	11276	74339	84.8%
Dublin County	339593	24082	90427	454102	80.1%

Sampling Strategy

The target sample were current members of a CSS in Dublin (GoCar), prospective members of a CSS in Dublin and Ireland (i.e. those who had at some point expressed an interest in joining GoCar) and potential members of a CSS, i.e. the population at large. GoCar, the only CSS operating in Dublin both at the time of the survey and currently, communicates with its membership via email list and newsletter. GoCar also maintained a separate mailing list for those who had expressed an interest in their service, as a potential member or for other reasons. The survey was distributed to these mailing lists as an item in the newsletter on 10th February 2012, and a subsequent reminder was sent via email on the 6th March 2012.

The survey was also distributed to the population at large by disseminating it through a range of media outlets, including social media, online forums targeting Ireland, radio, micro-blogging and Irish based popular news websites. Those completing the survey were encouraged to further distribute the survey via email and social media platforms.

A competition, open for six weeks, was used as an incentive and to reward respondents for participation. The total prize fund was €500, divided into two pots - €150 GoCar vouchers for GoCar members and €350 One4All vouchers for all respondents. Both competitions had a 1st prize

and a 2nd prize. These were €100 and €50 for the GoCar prize draw, and €250 and €100 for the main prize draw.

Survey Responses

The survey was conducted over a 6 week period between 10th February and 16th March 2012, and received 2,639 valid responses. These responses included 49 responses from members of GoCar. A summary of the survey results is presented in Section 4.5

3.5 Discussion

This chapter introduced the main sources of data used in this thesis, namely the POWSCAR dataset and the SAPS dataset (CSO, 2012a, 2012b). It also provided a detailed description of the methodology used to design and implement a survey to ascertain the travel spending and patterns of Irish residents.

3.5.1 Survey Results

The anonymity of an online survey facilitates low quality and/or inaccurate answers. Following recommended best practice guidelines the survey also did not make any individual question compulsory. Therefore many responses did not provide sufficient information or were not of sufficient quality to use. 3,488 individuals started the survey, and of these, 2,639 reached the final page and provided sufficient information for further analysis.

Table 3.6 Socio-Demographic Data on Survey Respondents

	Not Dublin		Dublin		Total
	No Car	Owns Car	No Car	Owns Car	
Age Brackets					
Under 18	36	1	80	3	120
18 - 23	198	39	614	89	940
24 - 50	160	277	486	461	1384
51-65	13	41	26	70	150
65+	1	3	4	5	13
NS	8	11	5	8	32
Principal Status					
Working for payment or profit	118	266	374	474	1232
Student or pupil	245	55	755	117	1172
Other	53	51	86	45	235

Table 3.6 provides an overview of the socio-demographic data provided by the 2,639 qualifying respondents. It illustrates that the survey attracted a large number of student respondents, which was not unexpected. In Chapter 5 and 7, only those who confirmed that they are working and of typical working age (18 – 65) are included in the journey calculations.

Figure 3.9 provides an overview of the number of journeys taken, the distance travelled and the time spent on each mode by respondents. The width of each box-plot indicates the number of respondents who used that mode in each case. The results show a large variation in the number of journeys reported by individuals on each mode of transport.

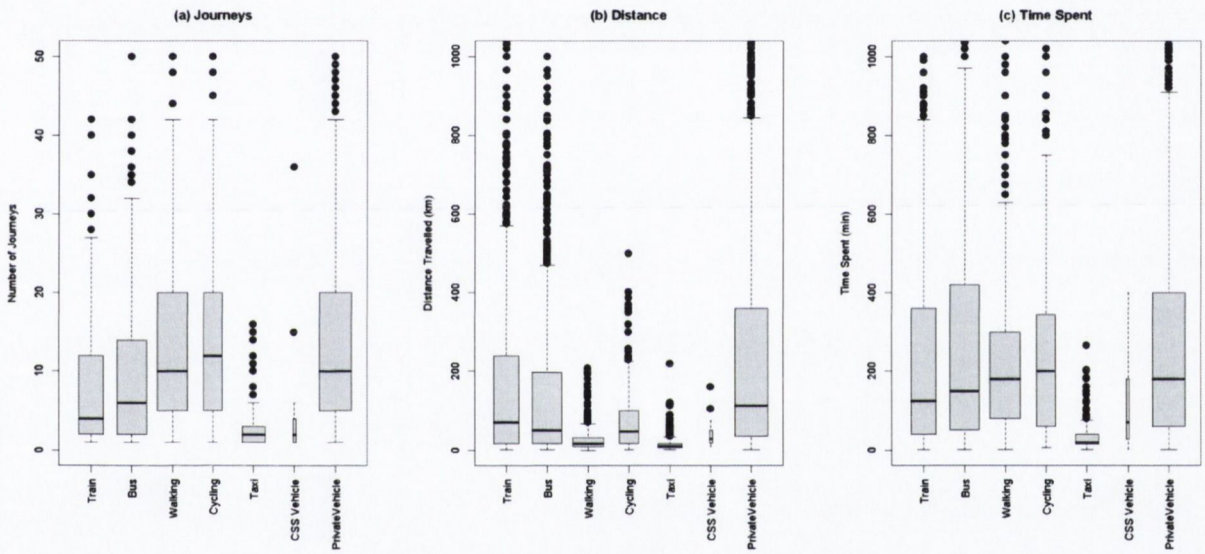

Figure 3.9: Per Fortnight, summary of (a) Number of Journeys Undertaken, (b) Distance Travelled and (c) Time Spent by Mode of Transport

3.5.2 GoCar Responses

A particular note needs to be made on the GoCar responses. As discussed in Section 3.4, the original intention in creating the survey was to compare the sustainability of the travel patterns of members of a CSS with those who had an interest in joining a CSS and with those who had no interest in joining the CSS. A concerted effort was made to recruit members of the CSS operating in Ireland (GoCar) at the time of the survey, through direct email contact facilitated by the company itself, notices in the services newsletter and by offering a large prize directly to members of the CSS.

However only 49 responses from the CSS were received. These responses described very low levels of usage, and provided incomplete socio-demographic data. Specifically 10 individuals declined to identify their place of residence. Of the remaining 39 responses, 31 lived in Dublin and 8 in Cork. Respondents also reported very low usage levels of the CSS. Of the original 49 respondents, 29 individuals reported making no rentals (18 Dublin Residents) in the survey period, and 7 individuals (4 Dublin Residents) reported making only 1 rental.

3.5.3 Change in Approach

As discussed in section 1.6.3, due to the low response rate, from GoCar users and the low usage rates the survey could not be used for its original purpose, however two similar studies were undertaken and these are described in the following chapters.

4 PRELIMINARY ANALYSIS OF SURVEY RESPONSES

This chapter analyses the survey responses to develop understanding of the sustainability of individual travel patterns in Ireland, including spending on domestic transport, the environmental impact of domestic transport and the relationship between travel patterns and individual wellbeing.

4.1 Introduction

This chapter describes the preliminary analysis carried out on the survey responses. These analyses were undertaken to derive useful information from the survey responses for use in the analysis of the economic and environmental impacts of car sharing and ride sharing. It also includes a brief exploration of the links between travel patterns and individual wellbeing found in the survey.

Section 4.2 details the methodology used to derive useful data regarding costs from the information provided by the respondents. An annual cost of travel is calculated for each respondent. This calculation is then used as the basis for the estimation of the economic impacts of a) car sharing in Chapter 5 and b) ride sharing in Chapter 7.

Section 4.3 details the methodology used to derive useful data regarding the CO_2 emissions from the information provided by respondents. An annual CO_2 emissions of travel is calculated for each respondent. This calculation is then used as the basis for the estimation of the environmental impact of a) car sharing in Chapter 5 and b) ride sharing in Chapter 7.

Section 4.4 briefly examines the relationship between social sustainability and transport, using the survey responses to investigate whether the proposed reduction in private car ownership and use is likely to have a negative impact on individual wellbeing.

Section 4.5 then provide a brief overview of the results of the survey and a summary of the chapter.

4.2 Cost Analysis of Survey Responses

Calculating an accurate figure for spending on travel was complex. As discussed in Section 3.4, transport users incur costs on a daily, weekly, monthly, annual and multi-year basis. In the case of

this survey, the direct costs of travel (fuel costs, maintenance costs, bus fares etc.) were recorded directly. The indirect costs related to vehicle ownership were then calculated separately. The methodology used to calculate the cost of travel in private vehicles and travel by public transport is described below.

4.2.1 Cost of Travel in Private Cars

The cost to an individual of travel in a private car can be divided into two categories, the costs associated with car ownership and the day to day running costs associated with use of the car. While survey respondents provided information on both of these areas, the information provided on the costs associated with vehicle ownership was problematic. The information provided by survey respondents included estimated depreciation, purchase payments and trade in values. This information was not broken down by vehicle, but covered all vehicles paid for by the respondent in the previous year. This presented difficulties when developing an equation to calculate the annual ownership costs. Therefore an alternative approach based on the methodology described by Hensher and Chen (2011) was developed.

For travel in private vehicles, Hensher and Chen (2011) estimate the cost of vehicle ownership by looking separately at five costs areas associated with vehicle ownership – depreciation, opportunity costs, annual fees and charges, tyres, and maintenance. The first two of these (depreciation and opportunity costs) are of interest here. Hensher and Chen (2011) used information provided by the National Roads and Motorists Association, Australia (NRMA) to estimate weekly costs per vehicle for a range of car engine sizes. Similarly data on car values provided by Irish Tax and Customs (2012a, 2012b) was used in conjunction with information provided by respondents on the age and engine size of the cars they owned to estimate each cars current value and subsequently the opportunity and depreciation costs of ownership. The remaining costs were then calculated using information provided by the respondents.

The calculation of ownership costs for private vehicles (i.e. opportunity and deprecation costs) first calculates the residual values of the cars based on the information provided by respondents. Two separate methodologies are used, and the choice of methodology depends on the age of the vehicle which respondents reported owning. Where respondents travelled in cars registered before July 2008, information was gathered about the year and engine size of the car in which they travelled. Where respondents travelled in cars registered after July 2008, information was gathered about the year and tax band of the car. This differentiation reflects motor taxation in

Ireland, which changed from a charge related to engine size before July 2008, to a charge related to CO_2 emissions thereafter and led to the difference in methodological approach. The following two sub-sections describe each of these approaches in turn and the full equation used to calculate the cost of car ownership is provided in the final sub-section.

Residual Car Value: Pre-July 2008

Where respondents owned a car registered before July 2008, the car's year of registration and engine size (provided by respondents) was used to estimate the value of the car. The estimated value was based on the most common make and model of that year and engine size in the Irish Car Fleet. The detailed methodology used for cars registered before July 2008 is now described.

The list of the Irish Car Fleet (see Section 3.2.2) as it stood in 2010 provided a break-down of the number of cars of each make, model and engine size by year of registration. This database was divided into groups by year, from 2000 – 2008 inclusive. A final group which included all years up to and including 1999 was also created. The Irish Tax and Customs VRT depreciation tables (Irish Tax and Customs, 2012b) provide depreciation rates up to 13 years, after which the tables ascribe a residual value of 3 – 9% of a cars original price. There was therefore limited benefit to examining in detail cars older than 1999. In addition few cars were identified as being of this age by respondents, e.g. 3.5% of respondents' cars were from 1999 vs. 7.2% in 2000 or 9% in 2006.

Each year's data was then analysed in turn. For engine sizes between 1,000ccs and 2,300ccs, the car make/models were divided into groups using 100cc increments of engine size. Two additional groups, less than 1,000ccs and greater then 2,300ccs were also used. For each year group & engine size combination, the most common make & model combination was identified, and an Open Market Selling Price (OMSP), Depreciation Code (DC), and CO_2/km figure was obtained from the Vehicle Registration Tax database (Irish Tax and Customs, 2012a).

The existence of sub-models presented problems for this approach. For instance a specific make and model may have a three door and five door version each with a different OMSP. Where a variety of sub-models existed in the VRT register (Irish Tax and Customs, 2012a) a popular online car sales website was utilised to identify the most common sub-models for the specific year & engine size & make & models (CarsIreland.ie, 2012).

Each respondent's car was assumed to be the most common make and model, for the year and engine size provided by the respondent. Using the OMSP, DC and current year for that make and

model, the equation used by the Irish Revenue to calculate each respondent's current car value was followed. (Irish Tax and Customs, 2012b).

Equation 4.1: Residual Car Value in a Specific Year (year)

(4.1)

Where:

- OMSP is the Open Market Selling Price, i.e. the value of the car when new.
- CC is the Condition Component. This is a reduction factor based on whether the car is well looked after. In line with the calculation guidelines provided by the revenue services, the condition of a respondent's car is assumed to be fair, and the condition component is therefore a reduction factor of 5%.
- MoP is the Month of Purchase component. This is an adjustment to the cars value based on the current month and the month in which the car was purchased. In line with data provided by the society of the Irish Motor Industry, March is adopted as the median month in which cars are purchased (see Figure 4.1). As the survey was also carried out in March, no month of purchase component was necessary, and a MoP of 1 was used throughout.
- DC is the Depreciation Component. The Irish Revenue provided a range of depreciation curves and the VRT database identifies the appropriate curve (Irish Tax and Customs, 2012a, 2012b). The appropriate depreciation component for each respondent's car was calculated using its age relative to 2012 and the assumed make/model of the car.

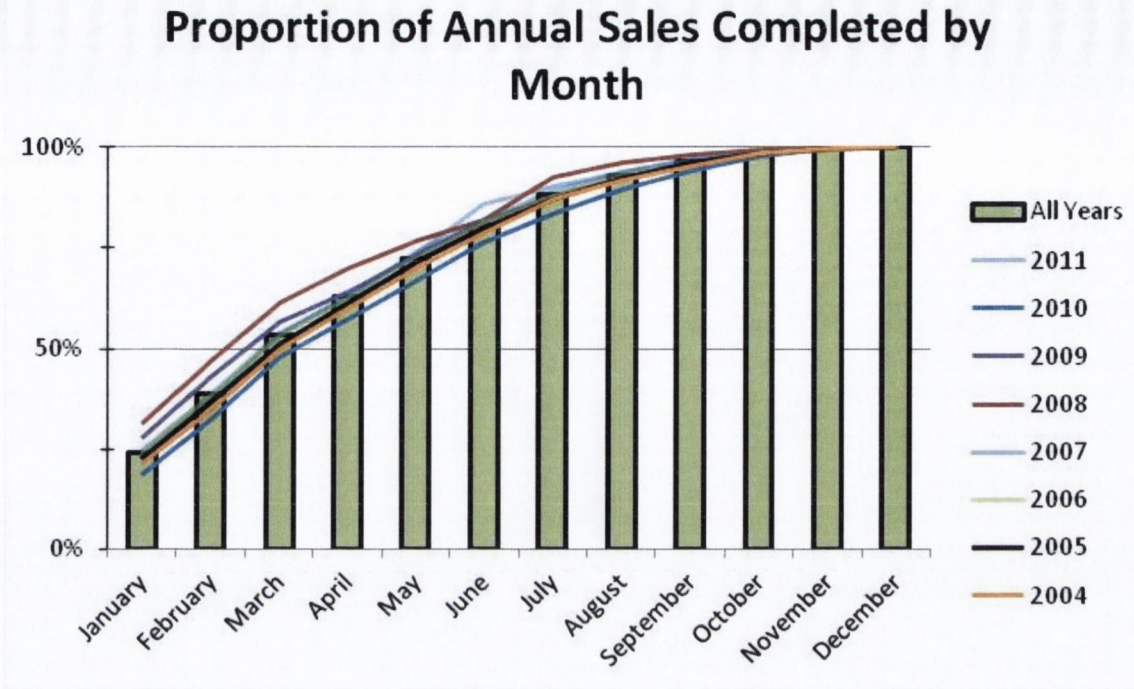

Figure 4.1: Proportion of Annual Car Sales Completed by Month

A second residual car value was also calculated based on value in one year's time. The procedure and equation for this was the same as for current car value, however the age was increased by one year.

As an example, a respondent who reported owning a 1000cc car, registered in 2002. The most common make and model for this engine size and year, was the Toyota Yaris, at 35.8% of vehicles. The VRT register (Irish Tax and Customs, 2012a) identified automatic and 3 door and 5 door versions of the Toyota Yaris. On April 12th 2012, all Toyota Yaris 998cc engines on CarsIreland.ie (2012) were manual, petrol and had five doors, this sub-model of the Toyota Yaris was therefore selected. This provided an OMSP of €12,861, a Depreciation Code of C1 and CO_2 emissions of 141g/km. For cars following depreciation curve C1, the VRT manual (Irish Tax and Customs, 2012b) then provides residual values of 19% and 13% for a ten and eleven year old car respectively.

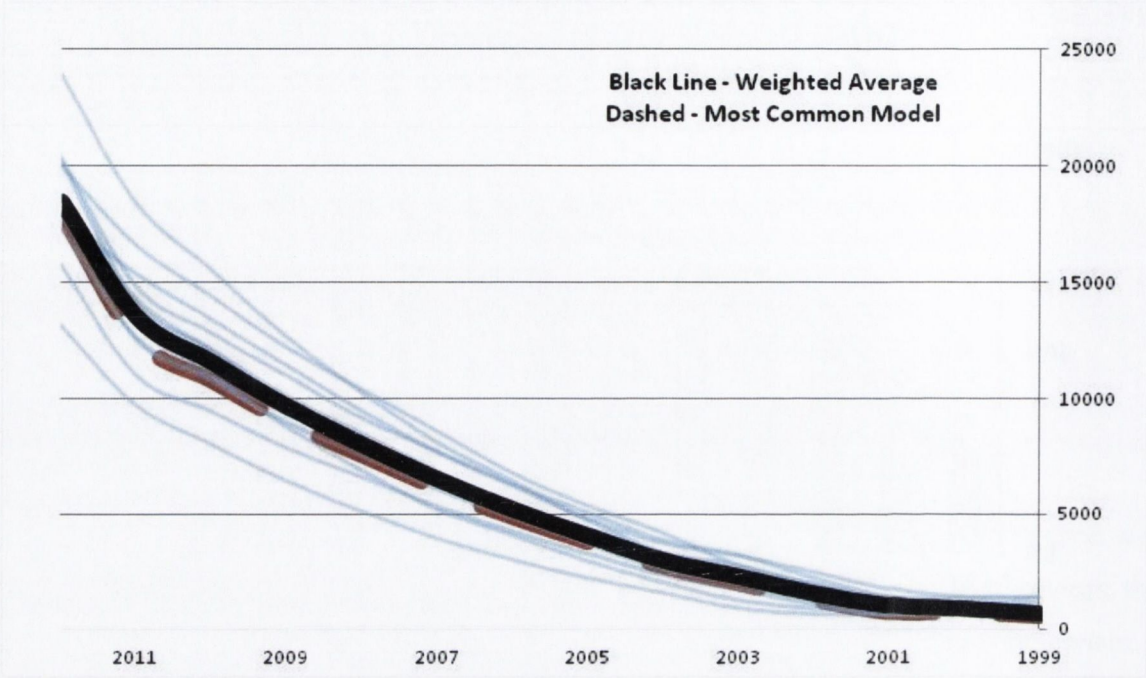

Figure 4.2: Depreciation Curves for most common 12, 1400cc engine sized/2008 cars on the road in 2010

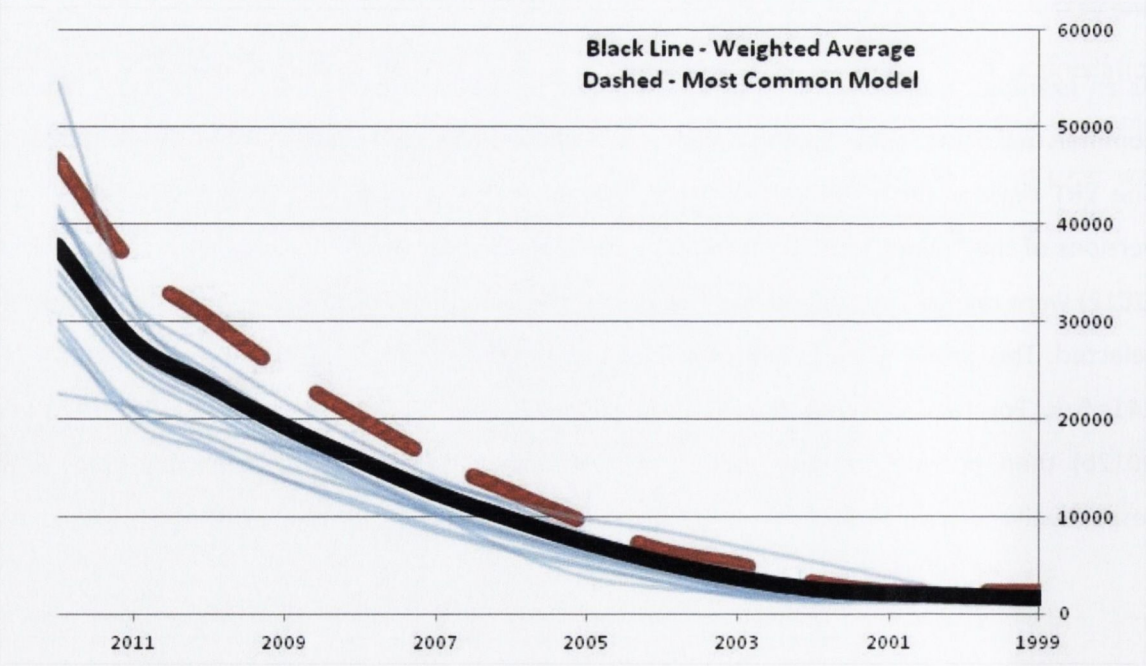

Figure 4.3: Depreciation Curves for most common 12, 1600cc engine sized/2008 cars on the road in 2010

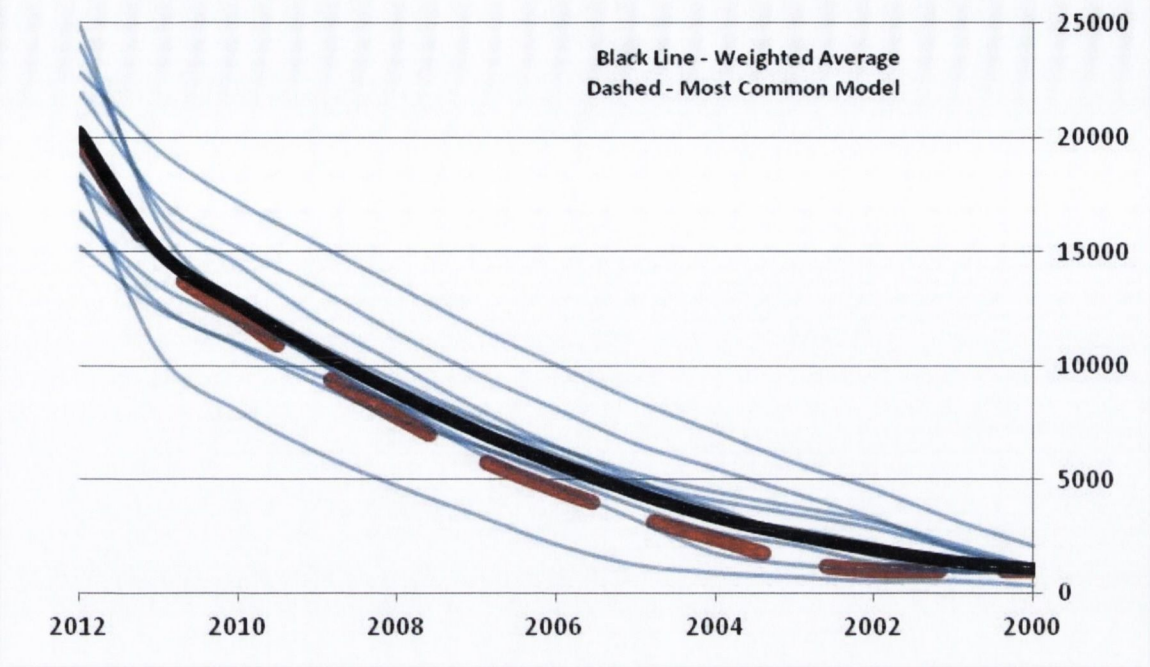

Figure 4.4: Depreciation Curves for most common 12, 2000cc engine sized/2008 cars on the road in 2010

For some categories of vehicle, e.g. 2001 cars with engine sizes 1000cc<x<1100cc, this produced a sample of 100% of that category's cars, for other groups, particularly the largest groups of 1400cc, 1600cc and 2000c, the sample size was less than 10%. To check the validity of the selected approach, the year 2008 was examined in more detail. The results of this process are shown in Figure 4,2, Figure 4.3 and Figure 4.4. These demonstrate that even where the most popular car represented only a small portion of the overall car fleet, the value obtained and the depreciation curve projected were closely related to the average value for that portion of the total fleet. Table 4,1 then summarises the results for each engine size and year.

Table 4.1 Average Residual Car Values in March 2012, for Cars Registered pre-July 2008

	Engine Size (cc)														
	1000	**1100**	**1200**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**	**1900**	**2000**	**2100**	**2200**	**2300**	**15000**
Pre - 2000	€755	€493	€576	€392	€690	€757	€823	€606	€747	€837	€863	€474	€1,634	€1,955	€3,220
2000	€881	€617	€744	€675	€716	€880	€962	€786	€1,060	€1,116	€1,079	€1,579	€2,079	€2,607	€3,220
2001	€1,636	€617	€924	€568	€716	€880	€962	€786	€1,022	€1,116	€1,997	€2,059	€2,059	€1,481	€4,026
2002	€2,391	€925	€1,453	€568	€1,254	€1,233	€1,346	€786	€1,022	€1,953	€1,145	€2,681	€2,059	€1,481	€2,750
2003	€2,894	€753	€2,379	€796	€1,970	€1,937	€1,393	€1,178	€5,592	€3,070	€1,431	€4,213	€3,094	€2,287	€4,553
2004	€2,367	€1,004	€2,509	€1,177	€2,687	€2,465	€2,388	€1,571	€8,388	€4,186	€2,963	€5,362	€5,663	€3,829	€12,353
2005	€3,156	€1,757	€3,301	€1,668	€4,324	€3,522	€3,383	€2,749	€9,182	€5,860	€4,198	€7,661	€6,429	€5,569	€4,670
2006	€4,077	€2,510	€3,313	€2,257	€4,836	€4,754	€4,577	€7,821	€4,609	€7,535	€5,679	€10,342	€10,852	€10,316	€10,599
2007	€4,998	€3,388	€5,649	€4,281	€6,572	€5,987	€5,970	€5,302	€17,071	€9,488	€15,885	€8,694	€13,302	€12,991	€14,573
2008	€6,181	€4,518	€6,690	€5,565	€7,523	€9,918	€7,761	€7,070	€11,049	€11,721	€20,090	€11,703	€16,453	€16,430	€26,787

Residual Car Value: Post-July 2008

Where respondents travelled in cars registered after July 2008, they provided details of the year and tax band of the car. The methodology used to estimate a respondent's cost of vehicle ownership was similar to that used pre-2008, however tax bands were used instead of engine size to calculate a weighted average value for selected makes and models. The methodology is detailed in full below.

The breakdown of the Irish Car Fleet in 2010 (described in Section 3.2) was divided into groups by year from 2008 – 2010 inclusive. As illustrated by in Table 3 of the Irish Bulletin of Vehicle and Driver Statistics Report 2010 (Department of Transport Tourism and Sport, 2011) there is greater variety in vehicle size and value within tax bands versus the engine size category used for the pre-July 2008 data. Therefore, the 30 most common car make/model/engine size combinations for each year group were identified. This provided a sample of almost 50% of the total fleet. A breakdown of the number of models which fell into each tax band category is provided in Table 4.2 below.

Table 4.2: Number of Models in Each Tax Band Category for Each Year Group

Tax Band	2008	2009	2010
A	4	5	12
B	10	11	10
C	8	10	4
D	4	3	3
E	3	1	1
F	1	0	0
G	0	0	0
% of Total Cars	45.5%	51.5%	54.8%

Purchases of cars in bands F and G are relatively rare, and this presented a problem, since no vehicles within these bands were included in the top 30 makes/models for either 2009 or 2010. By referring to Table 2 of the Irish Bulletin of Vehicle and Driver Statistics Report 2010 (Department of Transport Tourism and Sport, 2011), the most common engine size for Band F and G cars was identified as the 2,900cc – 3,000cc band. The most common car sold in that engine size between 2008 and 2010 was the BMW X5 2993cc, which was therefore selected as the representative model for years 2009 and 2010 where no Band F or G cars were in the top 30 makes/models sold.

In line with the methodology described in the pre-July 2008 section, the OMSP, DC and CO_2 emissions rating for each make/model/engine size were obtained from the VRT database (Irish

Tax and Customs, 2012a) and the current value and value in one year of each car make/model/year combination was calculated using Equation 4.1. These values were then used to calculate a weighted average current value and value in one year for each tax band and year. The difference between these two figures is the depreciation cost. The opportunity cost was calculated as 5% of the weighted current value.

The data on the car fleet was from 2010, which is the most recent available data, however the survey was carried out in February/March 2012. Using SIMI figures (SIMI, 2012) a comparison was made between the makes of cars sold in 2010 with those in 2011 and 2012. The comparison, shown in Table 4.3, demonstrates that overall market share for each make remains approximately constant between the years. The OMSP figures and depreciation curves used for 2010 are therefore applied to 2011 and 2012 and combined with an appropriate age to produce current values and value in one year amounts. These calculated values are summarised in Table 4.4.

Table 4.3: Market Share of Each Car Make, 2012 – 2010, derived from (SIMI, 2012)

	Market Share %		
Make	**2012**	**2011**	**2010**
AUDI	3.99%	3.71%	3.01%
BMW	3.75%	3.55%	2.76%
CITROEN	1.64%	1.34%	1.18%
FIAT	1.31%	0.93%	1.67%
FORD	10.93%	11.35%	12.41%
GM(OPEL)	6.22%	6.94%	7.31%
HONDA	1.13%	1.08%	1.31%
HYUNDAI	5.76%	4.24%	3.27%
KIA	3.78%	2.88%	2.84%
MAZDA	1.76%	1.95%	2.48%
MERCEDES-BENZ	2.27%	2.07%	2.28%
NISSAN	8.90%	7.29%	6.08%
PEUGEOT	2.85%	2.96%	3.24%
RENAULT	7.46%	9.32%	10.78%
SEAT	1.45%	1.91%	1.82%
SKODA	6.38%	5.05%	5.44%
TOYOTA	12.77%	12.67%	11.79%
VOLKSWAGEN	12.30%	12.18%	11.40%
VOLVO	1.42%	1.38%	1.02%

Table 4.4: Average Residual Car Values in March 2012, for Cars Registered post-July 2008

	Tax Band						
	A	B	C	D	E	F	G
Post July 2008	€ 7,292	€ 11,066	€ 10,588	€ 7,484	€ 8,472	€ 16,453	€ 42,922
2009	€ 7,769	€ 13,822	€ 14,579	€ 9,754	€ 9,750	€ 50,076	€ 50,076
2010	€ 12,571	€ 15,885	€ 14,076	€ 17,640	€ 11,184	€ 57,230	€ 57,230
2011	€ 14,530	€ 18,598	€ 16,374	€ 20,820	€ 13,568	€ 63,668	€ 63,668
2012	€ 17,586	€ 23,678	€ 20,634	€ 28,505	€ 18,335	€ 71,537	€ 71,537

Final Calculation of Costs of Travel in Private Vehicles

Following the calculation of residual car values using Equation 4.1 and the methodologies described above, the full cost of travel in private vehicles is then calculated by using the additional information provided by respondents.

First the opportunity cost and depreciation costs of car ownership are calculated by following Equation 4.2 (a) and (b) Where respondents indicated that they did not know the year, engine size or tax band of the car which they owned, the car was assigned a current value of €4,817.65, and a value in one year of €3,859.24. These values are a weighted average of the values estimated for respondents who provided full details of their cars.

Equation 4.2: Estimated (a) Opportunity Cost and (b) Depreciation Cost of Respondent's Car

$$\text{(a) } \delta_{opp} = \text{Car Value}_{year} * 5\% \qquad 4.2\text{ (a)}$$

$$\text{(b) } \delta_{dep} = \text{Car Value}_{year+1} - \text{Car Value}_{year} \qquad 4.2\text{ (b)}$$

The third compoent of private vehicle costs are the annual costs. These are the annual maintenance and running costs, which is calculated as the sum of the answers given by respondents for Motor Tax, Insurance, Maintenance and NCT and other expenses. That is answers (c) – (f) in the second question illustrated in Figure 3.3. The equation used is given in Equation 4.3.

Equation 4.3: Other Ownership Costs of Private Cars

$$\delta_{ann} = \text{Motor Tax} + \text{Insurance} + \text{Maintenance} + \text{Other Expenses} \qquad (4.3)$$

The final component of private vehicle costs are the day to day expenses of running a car. Respondents were asked to provided details of their spending on running costs (e.g. fuel) in the previous two weeks. Respondents were also asked to detail the amount which they could claim

back from other sources for travel costs incurred in the previous two weeks. The fortnightly running costs were then calculated using Equation 4.4.

Equation 4.4: Fortnightly Cost of Travel in Private Cars

$$\delta_{exp} = \text{Spending on Fuel} - \text{Expenses Reclaimed} \quad (4.4)$$

4.2.2 Cost of Travel by Public Transport

The information provided for travel by public transport and in taxis was considered to be sufficient to make a direct calculation. The ticketing costs paid detailed by respondents were added together to give two figures for costs of public transport. These details were provided in answer to the question shown in Figure 3.7. The Equations used to calculate the cost of travel via public transport are given in Equation 4.5 below.

Equation 4.5: (a) Annual and (b) Fortnightly costs associated with Travel using Public Transport

a) β_{ann} =Annual Tickets + Tax Saver Tickets + (Monthly Tickets*12)+(30 Day Tickets*12) 4.5(a)

b) β_{exp} = (Weekly Tickets) + ((Cost of Ten Journey Ticket/10)*Number of Journeys Used) + Other Travel Tickets 4.5(b)

4.2.3 Final Equation for Cost of Travel

As shown in Equation 4.6, the opportunity and depreciation costs for each respondent were then combined with the other cost of travel information provided, to obtain an Annual Travel Cost for each respondent.

Equation 4.6: Annual Travel Cost Calculation

(4.6)

Where δ_{opp}, δ_{dep} are the calculated opportunity and deprecation costs respectively, δ_{ann} and δ_{exp} are the directly reported annual and fortnightly costs of private vehicle travel; β_{ann} and β_{exp} are the directly reported annual and fortnightly costs of travel on public transport and θ_{oth} are the directly reported fortnightly costs of taxi travel, GoCar travel and a pro-rata figure for GoCar monthly membership.

4.3 Carbon Dioxide Analysis of Survey Responses

Calculation of CO_2 emissions of travel was based on the distance travelled by individuals on each mode of transport. Where possible, the CO_2 emissions of travel in private cars were calculated

based on the year and engine size or tax band details provided by respondents. Where respondents did not provide sufficient details of the car in which they travelled, an average value of 147.3g/km was obtained from the weighted average of all car details provided by respondents. CO_2 emissions per km for other modes were taken the CMT emissions calculator (Environmental Protection Agency, 2009). A full list of the CO_2 emissions rates used is provided in Table 4.5 below. The CMT emissions calculator also provides a value of 150g/km travelled for an average private car in Ireland. This is therefore adopted as the emissions value of a vehicle owned by the Car Sharing Service.

Table 4.5: Carbon Dioxide Emissions of Transport Modes

Mode of Transport	CO_2 emissions (g/km travelled)	Mode of Transport	CO_2 emissions (g/km travelled)
Bus	77	Motorcycle <75cc,	72.9
Train	44.3	Motorcycle >75cc	93.9
Cycling	0	Taxi	168.5
Walking	0	Private Car	147.3

4.4 Wellbeing Analysis of Survey Responses

The primary focus of this thesis is on improving the sustainability of transport by reducing reliance on private vehicles. The environmental and economic impacts are examined in detail in later chapters. This section briefly examines the relationship between social sustainability and transport, investigating whether the proposed reduction in private car ownership and use is likely to have a negative impact on individual wellbeing.

A subset of responses to the survey is used to analyse each respondent's travel with respect to wellbeing and health. Section 4.4.1 describes the sub-samples used for this analysis and summarises the principle characteristics of these sub-samples. The measures analyzed include responses provided directly by respondents and figures for cost of travel and CO_2 emissions of travel calculated from responses to the survey using the methodology described in Section 4.2 and Section 4.3 respectively.

Section 4.4.2, 4.4.3 and 4.4.4 then describe the analysis of the data. The work was carried out in three stages. Following a preliminary analysis, a more detailed analysis was carried out in two parts which are loosely based on the model proposed by Delbosc (2012) and discussed in Section 2.4. These two parts are transport mobility and transport accessibility.

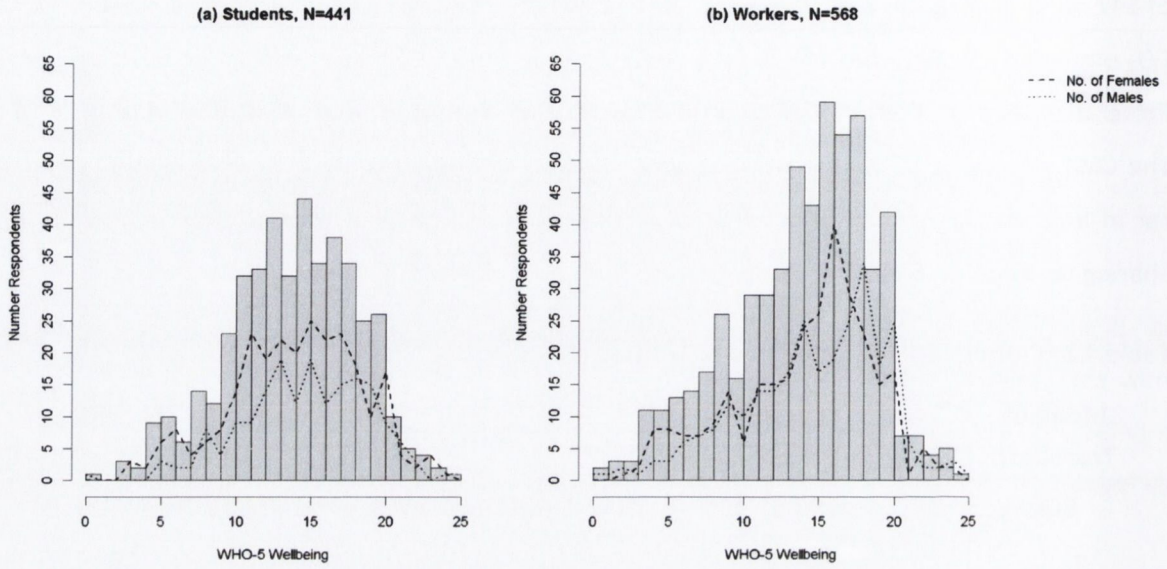

Figure 4.5: Distribution of WHO-5 Wellbeing Score

4.4.1 Sub-Sample Characteristics

The criteria used to select the two samples of interest were based on the desire to have relatively homogenous sub-samples. The sample was first restricted to residents of Dublin and those who confirmed that the travel pattern described in the responses was typical of their normal patterns.

The first sub-sample then extracted was students in the 18 – 23 age range. These individuals are close in age, relatively fit and healthy, and possess the same level of education. The second sub-sample extracted was those who reported themselves as being between the age of 18 and 60, and having a principal economic status of "*Working for payment or profit*". As the literature described in Section 2.4 indicates, work status is strongly correlated with wellbeing, unemployment has a severe negative impact on wellbeing, while retirement is associated with old age and thus ill health and lowered wellbeing. By removing these major sources of variation in wellbeing from the sub-samples we expect to be better able to examine the influence of transport behaviour on wellbeing. Summary statistics for both samples are presented in Table 4.6 and Figure 4.5 presents the distribution of WHO-5 Wellbeing Score for each sample.

Table 4.6: Description of Survey Data

		Student			Worker		
		Female	Male	Total	Female	Male	Total
Personal and Household Characteristics							
	Population	261	180	441	292	276	568
	% Population	59.2%	40.8%		51.4%	48.6%	
Mean Household Size (S.D)		3.9 (1.4)	4 (1.5)	3.9 (1.4)	2.4 (1.1)	2.6 (1.2)	2.5 (1.2)
	No. Adults	3.4 (1.2)	3.4 (1.3)	3.4 (1.2)	2.1 (0.9)	2.1 (0.9)	2.1 (0.9)
Health and Wellbeing Indicators							
WHO-5 Wellbeing Score (S.D)		14.0 (4.3)	14.7 (4.2)	14.3 (4.3)	14.1 (4.6)	14.6 (4.7)	14.3 (4.7)
Health Score (N = . . .)	**Very Good**	77	58	135	103	83	186
	Good	151	96	247	152	146	298
	Poor	33	26	59	37	47	84
Mean and (Standard Deviation) of Annual Travel Use Characteristics							
	Journeys	940.4 (485.4)	934.7 (469.7)	938.1 (478.5)	943.9 (439.9)	916.3 (439.9)	930.5 (439.7)
	Time Spent (Hours)	361.3 (196.9)	318.4 (169.2)	343.8 (187.1)	327.6 (171.7)	303.1 (166.4)	315.7 (169.5)
	Distance (Km)	8623.1 (7001.4)	7381.6 (5920.9)	8116.4 (6603.1)	7273.2 (6110)	8255.3 (6847.9)	7750.4 (6491.9)
	Transport Cost (€)	1618.5 (1463)	1407.6 (1547.9)	1532.4 (1500.1)	3027.5 (2300.3)	3503.9 (2967.5)	3259 (2653.9)
	CO_2 Emissions (Kg)	551.7 (552.8)	441.3 (515.5)	506.6 (540.0)	547.3 (609.9)	653.2 (744.4)	598.7 (680)
Mode Use Characteristics							
	Used Bus	81%	67%	75%	59%	53%	56%
	Used Train	54%	48%	51%	45%	46%	45%
	Used Car	77%	71%	75%	81%	78%	80%
	Walked	76%	70%	73%	71%	68%	70%
	Cycled	20%	42%	29%	28%	43%	35%
Transport Access Characteristics							
	No. Of Modes Used (of 5), (S.D.)	3.1 (0.9)	3 (1.1)	3.0 (1.0)	2.8 (0.9)	2.9 (1.1)	2.9 (1)
	No. Of Modes for Access to Work/College (S.D.)	2.6 (1.2)	2.8 (1.2)	2.7 (1.2)	2.7 (1.1)	2.7 (1.2)	2.7 (1.1)
	Vehicle Ownership	12%	10%	11%	59%	52%	55%

The large standard deviations in travel characteristics indicate a large variability between individual respondents travel patterns. The overall travel characteristics of males and females are broadly similar; however several differences emerge between the student and worker sub-samples, in particular students and workers have different costs of transport and reported levels of CO_2 emissions. This is explained by higher levels of car ownership and use among the working population. The student sample has more females (N=261) than males. In both samples, there is also a noticeable difference between the numbers of male and female cyclists. In terms of

transport access, the average number of modes used at least once in the preceding two weeks was the same across all groups, as was the number of "realistic" ways to get to work or college.

Each survey respondent provided details of the number of journeys taken, the number of minutes spent and the distance travelled on each mode of transport (bus, train, walking, cycling, car share vehicles, taxi and private vehicle). This data was used to calculate values for total annual travel. When examining the usage of different modes those making 10 or more journeys using a particular mode are defined as being frequent users.

To allow further examination of the modes by which respondents could access their place of work or education, the questionnaire asked:

> *"Realistically what ways could you use to travel to your place of work or education? Consider your health, availability of parking, bus timetables, the time you need to arrive and depart, how long it would take etc."*

And gave: car, bus, train, cycling and walking as options. Respondents were asked to choose all that applied.

The question on health is taken from question 18 of Irish Census 2011 (CSO, 2011f) which asked: "How is your health in General?" and offered five answer options: Very good, Good, Fair, Bad and Very bad. Due to the low number of people who reported Bad (N=9) and Very Bad (N=0) health, those reporting fair, bad and very bad health were re-categorised into a single category: Poor.

The WHO-5 question set is used to analyse wellbeing. The WHO-5 wellbeing test consists of five positively worded statements, for which respondents are asked to rate their feelings over the last two weeks, on a six point Likert Scale, from *all of the time* (5pts) to *at no time* (0pts). The maximum score is 25pts, representing high wellbeing and the minimum score is 0pts. (Bech, 2004) To assist the analysis, respondents were categorised into four ordinal categorical variables, ranked from Happiest to Saddest, according to the quartiles of the wellbeing score. This resulted in the divisions presented in Table 4.7 below.

Table 4.7: Ordinal WHO-5 Wellbeing Categories

	Students			Workers		
	Range	N	%	Range	N	%
Great	(25-17)	145	33%	(25-18)	156	27%
Happy	(16-15)	78	18%	(17-15)	156	27%
Ok	(14-11)	138	31%	(14-11)	140	25%
Sad	(10-0)	80	18%	(10-0)	116	20%
Total		441	100%		568	100%

4.4.2 Preliminary Analysis

This section examines the relationship between the personal and household characteristics of respondents and their wellbeing. Pearson's chi-square tests were carried out to test whether the frequency distribution of wellbeing ratings (Great – Sad) and health (Very Good - Poor), matched the null hypothesis, that there is no difference between respondents reporting different personal characteristics. One way ANOVA tests were also used to test for differences in wellbeing levels (0-25pt WHO-Scale) with respect to the personal characteristics of respondents.

Table 4.8 presents the results of the personal and household characteristics analysis of the two sub-samples. As expected a significant link ($p<0.01$) is found between wellbeing and health. The Pearson's chi-Squared test also identifies a significant link between the gender of workers and their wellbeing on the 25pt WHO scale. However under a student's t test, females who worked reported a lower wellbeing ($M=14.1$, $SD = 4.6$) than males ($M=14.6$, $SD = 4.7$). This difference was not significant $t(433)=-0.25$, $p =0.80$. Figure 4.5 illustrates what is actually happening with regards to the different distribution of wellbeing between male and female workers. It shows that while the female sub-sample has a sharp peak at 15, the male subsample is more widely distributed with three smaller peaks at 14, 17 and 19. No other links between the personal characteristics of workers or students and (a) wellbeing or (b) health were identified.

Table 4.8: Workers and Students Personal and Household Characteristics Vs. Wellbeing And Health

	Pearson's Chi-Squared Test						ANOVA Tests			
	Health			Wellbeing			Wellbeing			
							Deg. of Freedom			
	df	$\chi2$	ρ	Df	$\chi2$	ρ	Btwn. Groups	W/in Groups	F Value	ρ
Students										
Gender	2	0.9	0.64	3	2.2	0.53	1	439	2.8	0.10
Household Size	10	7.9	0.64	15	9.0	0.88	5	435	0.9	0.48
Number of Adults	10	8.5	0.58	15	14.4	0.49	5	435	0.9	0.49
Children (Yes/No)	2	0.2	0.90	3	5.7	0.13	1	439	2.8	0.10
Health	-	-	-	6	97.1	0.00				
WHO 5	6	89.3	0.00**	-	-	-				
Workers										
Gender	2	3.0	0.22	3	11.9	0.01**	1	566	2.1	0.15
Household Size	10	11.9	0.29	15	11.8	0.70	5	562	1.1	0.37
Number of Adults	10	17.5	0.06	15	13.3	0.58	5	562	0.8	0.58
Children (Yes/No)	2	1.8	0.41	3	0.8	0.84	1	566	0.0	0.84
Age	14	9.0	0.83	21	25.4	0.23	7	560	1.3	0.24
Health	-	-	-	6	97.1	0.00**				
WHO 5	6	97.1	0.00**	-	-	-				

***significant at ρ<0.01*

4.4.3 Transport Mobility

Under mobility, Delbosc's (2012) model proposes that freedom to travel and active transport may have an influence on subjective wellbeing. In this section the relationship between the modes of travel respondents reported using and their wellbeing is analysed.

Two statistical tests were performed, namely the Pearson's Chi Square Test and the Student's t test. Pearson's chi-Square Tests were carried out to test whether the frequency distribution of wellbeing ratings (Great – Sad), and health ratings (Great, Very Good, Poor) matched the null hypothesis, that there is no difference between wellbeing for those who use a specific mode of transport vs. those who do not. Tests were carried out for each mode of transport, on those who used the mode once or more and on those who used the mode ten or more times in the two week survey period. A t-test was also used to determine whether the mean WHO-5 Score (1-25pt scale) differed between those who reported using a specific mode of transport and those who did

not. The full results are presented Table 4.9 and Table 4.10 respectively. The results indicate a relationship between wellbeing and cycling but do not indicate a link between private vehicle usage and wellbeing. Further research is needed to establish the relationship between wellbeing and cycling, i.e. whether those with higher wellbeing choose to cycle or whether cycling induces higher wellbeing.

Table 4.9: Pearson's Chi-Squared Test Results Comparing Wellbeing and Health among Users and Frequent Users of Different Transport Modes

	Wellbeing					Health				
		Used Once		Used Often			Used Once		Used Often	
	df	χ^2	ρ	χ^2	ρ	df	χ^2	ρ	χ^2	ρ
Students										
Bus	3	6.06	0.11	7.55	0.06	2	1.85	0.40	7.70	0.02*
Train	3	8.16	0.04*	8.72	0.03*	2	1.12	0.57	3.62	0.16
Car	3	3.59	0.31	2.29	0.51	2	0.50	0.78	0.49	0.78
Other	-	-	-	-	-	-	-	-	-	-
Walked	3	1.81	0.61	4.51	0.21	2	0.32	0.85	0.58	0.75
Cycled	3	11.11	0.01*	15.98	0.00**	2	10.51	0.01*	14.56	0.00**
Taxi & GoCar	3	5.77	0.12	-	-	2	4.42	0.11	-	-
Workers										
Bus	3	1.35	0.72	7.91	0.05*	2	5.60	0.06	2.41	0.30
Train	3	3.00	0.39	3.23	0.36	2	2.29	0.32	0.50	0.78
Car	3	0.21	0.98	1.74	0.63	2	4.92	0.09	2.87	0.24
Other	3	0.87	0.83	0.64	0.89	-	-	-	-	-
Walked	3	3.30	0.35	9.28	0.03*	2	2.04	0.36	0.99	0.61
Cycled	3	10.93	0.01*	15.93	0.00**	2	3.02	0.22	6.05	0.05*
Taxi & GoCar	3	6.41	0.09	-	-	2	1.78	0.41	-	-

** Significant at ρ<0.05, ** significant at ρ<0.01*

Table 4.10: Students t-Test Results Comparing Wellbeing among Users and Frequent Users Of Different Transport Modes

	Used At Least Once						Used Often (10 or More Journeys)					
	N	Mean Used (S.D.)	Mean No Use (S.D)	T	df	ρ	N	Mean Used (S.D.)	Mean No Use (S.D)	T	df	ρ
Students												
Bus	332	14.0 (4.1)	15.1 (4.7)	-2.18	165.1	0.03*	148	13.4 (4.2)	14.7 (4.3)	-3.00	297.6	0.00**
Train	227	14.1 (3.8)	14.4 (4.7)	-0.58	408.9	0.56	80	13.5 (3.8)	14.4 (4.4)	-1.91	131.0	0.06
Car	330	14.1 (4.2)	14.8 (4.4)	-1.54	183.9	0.13	109	13.8 (4.3)	14.4 (4.3)	-1.39	182.3	0.17
Other	10	-	-	-	-	-	2	-	-	-	-	-
Walk	324	14.5 (4.1)	13.7 (4.7)	1.52	184.1	0.13	212	14.7 (4.2)	13.9 (4.3)	1.93	438.0	0.05
Cycle	128	14.9 (4.3)	14.0 (4.3)	2.07	233.3	0.04*	91	15.2 (4.5)	14.0 (4.2)	2.24	132.7	0.03*
Taxi	167	13.9 (4.1)	14.4 (4.4)	-1.23	365.5	0.22	0	-	-	-	-	-
Workers												
Bus	320	14.1 (4.7)	14.6 (4.6)	-1.38	537.3	0.17	108	13.5 (5.3)	14.5 (4.5)	-1.82	144.8	0.07
Train	258	14.0 (4.8)	14.6 (4.5)	-1.33	535.9	0.18	101	13.7 (4.9)	14.5 (4.6)	-1.49	140.9	0.14
Car	452	14.3 (4.7)	14.6 (4.5)	-0.78	182.6	0.43	237	14.2 (4.7)	14.4 (4.7)	-0.56	507.7	0.57
Other	30	15.0 (4.4)	14.3 (4.7)	0.85	32.7	0.40	11	-	-	-	-	-
Walk	395	14.1 (4.7)	14.9 (4.5)	-2.00	340.6	0.05*	257	13.7 (4.5)	14.8 (4.7)	-2.77	553.9	0.01**
Cycle	201	15.2 (4.3)	13.9 (4.8)	3.29	454.0	0.00**	134	15.8 (4.1)	13.9 (4.7)	4.64	249.4	0.00**
Taxi	257	14.4 (4.2)	14.2 (5)	0.49	565.8	0.63	2	-	-	-	-	-

** Significant at ρ<0.05, ** significant at ρ<0.01*

This study is focused on reducing reliance on private vehicles; therefore this section now examines car usage in more detail.

A t-test comparing the mean wellbeing score of workers who owned cars with those who did not, found that those who owned cars were slightly happier (M=14.4, SD = 4.6) than those who did not (M=14.3, SD = 4.6), however this difference was not found to be significant t(543)=0.17, p = 0.836.

For students, those who owned cars were slightly less happy (M=13.8, SD=4.3) than those who did not (M=14.3, SD=4.3) but the difference was not statistically significant t(61)= -0.82, p=0.77.

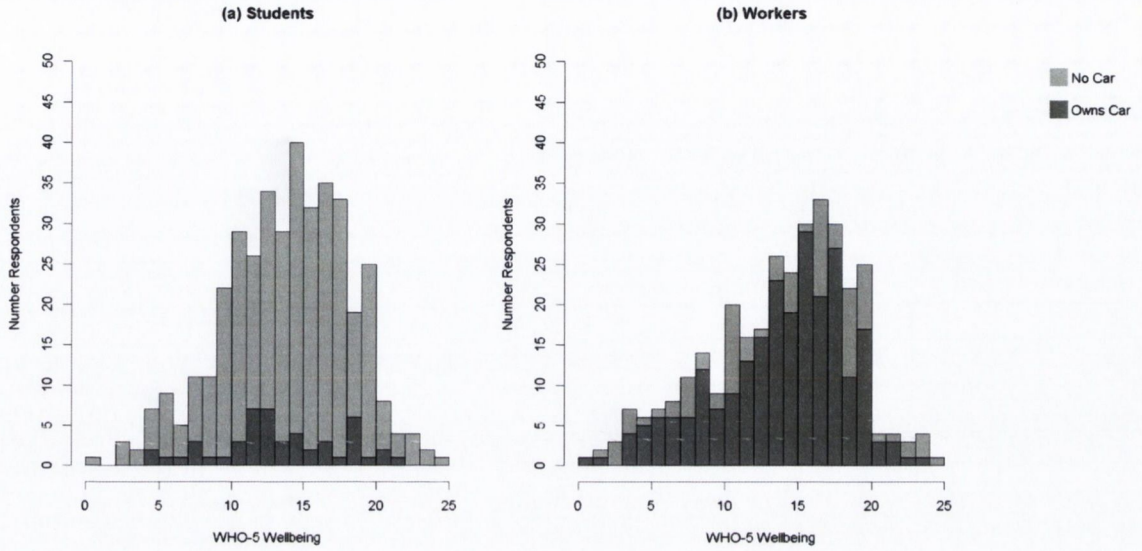

Figure 4.6: Comparison of WHO-5 Wellbeing levels for (a) Students and (b) Workers who own and do not own cars.

Table 4.11: Students t-Test Results Comparing Wellbeing among Car Owners and Non-Car Owners by Levels of Car Usage

	N Used	Mean Used (S.D.)	Mean No Use (S.D)	T	df	ρ
Students who own a Car, N=49						
Used Car at Least Once	47	13.7 (4.3)	16.0 (4.2)	-0.76	1.09	0.58
Used Car Frequently	31	13.1 (4.7)	14.9 (3.4)	-1.52	44.76	0.13
Students who don't own a Car, N=392						
Used Car at Least Once	283	14.1 (4.2)	14.8 (4.4)	-1.32	189.27	0.19
Used Car Frequently	78	14.0 (4.2)	14.4 (4.3)	-0.73	121.35	0.47
Workers who own a Car, N=315						
Used Car at Least Once	306	14.4 (4.7)	11.9 (5.2)	1.46	8.39	0.18
Used Car Frequently	199	14.1 (4.7)	14.8 (4.6)	-1.25	243.73	0.21
Workers who don't own a Car, N=253						
Used Car at Least Once	146	13.9 (4.7)	14.9 (4.4)	-1.68	235.50	0.09
Used Car Frequently	38	14.7 (4.4)	14.2 (4.7)	0.58	52.74	0.56

This is illustrated in Figure 4.6 which provides histograms of the WHO-5 wellbeing scores of workers and students who reported owning and not owning cars. As the figure demonstrates, the

distribution of wellbeing scores is similar for both groups, although few students report owning cars. Table 4.11 compares wellbeing, car ownership status and differing frequencies of car usage. For both the worker and student sub-samples, car use, whether frequent or infrequent, no significant links between car ownership, car use and wellbeing are identified.

4.4.4 Transport Accessibility and Use

Pearson's chi-square tests were carried out to test whether the frequency distribution of wellbeing ratings (Great – Sad), and health ratings (Great, Very Good, Poor) matched the null hypothesis, that there is no difference between wellbeing and health for those who have access to work via a specific mode of transport vs. those who do not. A t-test was also used to determine whether the mean WHO-5 Score (1-25pt scale) differed between those who reported access to a specific mode of transport and those who did not. The results of these analyses are presented in Table 4.12 below.

Table 4.12: Pearson's Chi Squared and t-Test Results Comparing Wellbeing and Health among Respondents Who Report Access To A Mode For Travel To Work Or College

	Pearson's Chi Squared Tests						Student's t-test					
	Health			Wellbeing			Wellbeing					
	df	χ^2	ρ	df	χ^2	ρ	N Access	Mean w/ Access (S.D.)	Mean w/o Access (S.D)	T	df	ρ
Students												
Bus	2	0.65	0.72	3	11.01	0.01*	345	13.9 (4.1)	15.4 (4.8)	-2.84	135.1	0.01**
Train	2	0.20	0.90	3	9.39	0.02*	162	13.8 (4.0)	14.5 (4.4)	-1.56	365.8	0.12
Car	2	6.27	0.04*	3	1.48	0.69	137	13.9 (4.3)	14.4 (4.3)	-1.01	258.0	0.31
Walk	2	0.01	0.99	3	2.80	0.42	234	14.5 (4.2)	14.0 (4.4)	1.31	429.1	0.19
Cycle	2	10.74	0.00**	3	0.43	0.93	299	14.2 (4.2)	14.3 (4.5)	-0.03	257.5	0.98
Workers												
Bus	2	0.96	0.62	3	8.41	0.04*	345	14.8 (4.5)	13.6 (4.9)	2.81	444.7	0.01**
Train	2	1.29	0.52	3	0.44	0.93	190	14.3 (4.6)	14.4 (4.7)	-0.22	388.4	0.83
Car	2	0.36	0.84	3	10.17	0.02*	325	14.8 (4.4)	13.7 (5.0)	2.82	481.3	0.00**
Walk	2	2.48	0.29	3	2.42	0.49	286	14.5 (4.6)	14.1 (4.7)	1.10	565.0	0.27
Cycle	2	3.94	0.14	3	12.58	0.01**	401	14.8 (4.5)	13.3 (4.9)	3.38	287.4	0.00**

** Significant at ρ<0.05, ** significant at ρ<0.01*

Examining the results related to car travel it is found that those who can access work via car report significantly higher wellbeing than those who cannot. In a final set of analyses the link between car ownership, car access (taking one more journeys in a private car during the study period) and no car access was investigated. A Pearson's chi-squared test carried out using three levels of car access (Car Ownership, Car Use Reported at Least Once, No Car Use) and the wellbeing categorical variable set, also found no significant difference between wellbeing for each level of car access, for either students or workers.

4.5 Discussion

The aim of this chapter was to contribute to understanding of the environmental, economic and social impacts of individual travel patterns of through the analysis of the survey results. The chapter described the methodology developed to calculate a cost and CO_2 emissions of travel for each survey respondent. These results are used in Chapters 5, 6 and 7. In each of these chapters, the analysis conducted uses a specific subset of the survey data. A more comprehensive overview of the survey data in these subsets is given in the relevant chapter. The key findings of this chapter are now presented.

4.5.1 Cost of Travel and CO_2 emission

The results of the analysis of the cost of travel and CO_2 emissions for groups of respondents are summarised in Table 4.6 and in Table 4.13. Additional breakdowns specific to workers in Dublin are provided in Table 5.3 and Table 5.6.

Table 4.13: Breakdown of Annual Cost and CO_2 of Travel for Survey Respondents

		Not Dublin		Dublin		Total
	Symbol	No Car	Owns Car	No Car	Owns Car	
N		416	372	1215	636	2639
Opportunity Costs of Car Ownership	δ_{opp}	€-	€360.31	€-	€306.20	€124.58
Depreciation Costs of Car Ownership	δ_{dep}	€-	€1,390.81	€-	€1,212.46	€488.26
Annual Contributions towards all PV	δ_{ann}	€184.50	€1,262.95	€134.20	€1,115.86	€537.82
Fortnightly Costs for Travel in PV	δ_{exp}*26	€498.44	€2,324.08	€293.46	€1,555.14	€916.08
Annual Train and Bus Tickets Cost	β_{ann}	€353.53	€289.48	€286.62	€162.20	€267.59
Fortnightly costs for travel in buses and trains	β_{exp}*26	€823.40	€259.29	€434.09	€275.28	€432.55
Annual Taxi Spend	θ_{oth}	€243.84	€142.81	€248.26	€259.19	€235.33
Total Travel Cost		€2,103.72	€6,029.74	€1,396.63	€4,886.33	€3,002.21
Carbon Dioxide Emissions	(kg/yr)	1192.1	3365.2	794.1	1023.8	1274.6
Distance/Year	(km)	15,148	21,334	7,992	11,687	11,891
Cost/km	(€/km)	€0.14	€0.28	€0.17	€0.42	€0.25
CO_2/km	(g/km)	79	158	99	88	107

In the following chapter these survey results and datasets are also be used to evaluate the impacts of introducing a car sharing service to Ireland, and a ride sharing service to Dublin. The observed costs and emissions for the subset of survey respondents who work in Dublin are therefore presented in Table 5.6. Each of these tables highlight the high cost and environmental impact of car ownership.

5 THE FEASIBILITY AND POTENTIAL BENEFITS OF ORGANISED CAR SHARING IN IRELAND

A version of this chapter has previously been published in Transportation Research Part D: Transport and the Environment (Rabbitt & Ghosh, 2013)

5.1 Introduction

For Ireland to meet Kyoto targets, a reduction in transport related carbon dioxide emissions is required. Internationally Car Sharing (CS) has been identified as a potential means of promoting sustainable travel modes, thus reducing emissions, while still allowing members the benefits of car access. In this chapter we develop a methodology to evaluate the potential of CS to reduce transport CO_2 emissions at a population level, using Ireland and Dublin as a case study. The methodology evaluates the potential of CS through the use of multiple alternative scenarios which examine the geographic, financial and environmental factors influencing CS adoption. The scenarios were developed using a conservative approach throughout and were designed based on existing research and observations from existing Car Sharing Services (CSS). These scenarios were then applied to the available and collected travel information of the Irish population to estimate the potential impact of introducing CS in Ireland.

The rest of this chapter is laid out in three sections, which provide the methodology for the analysis (Section 5.2), the results of the analysis (Section 5.3) and a brief discussion of the results (Section 5.4). Both the methodology and the results sections are further divided into three sections which each describe a phase of the analysis. These three phases are a geographic analysis, an economic and environmental analysis, and an overall analysis which combines the results of the first two phases.

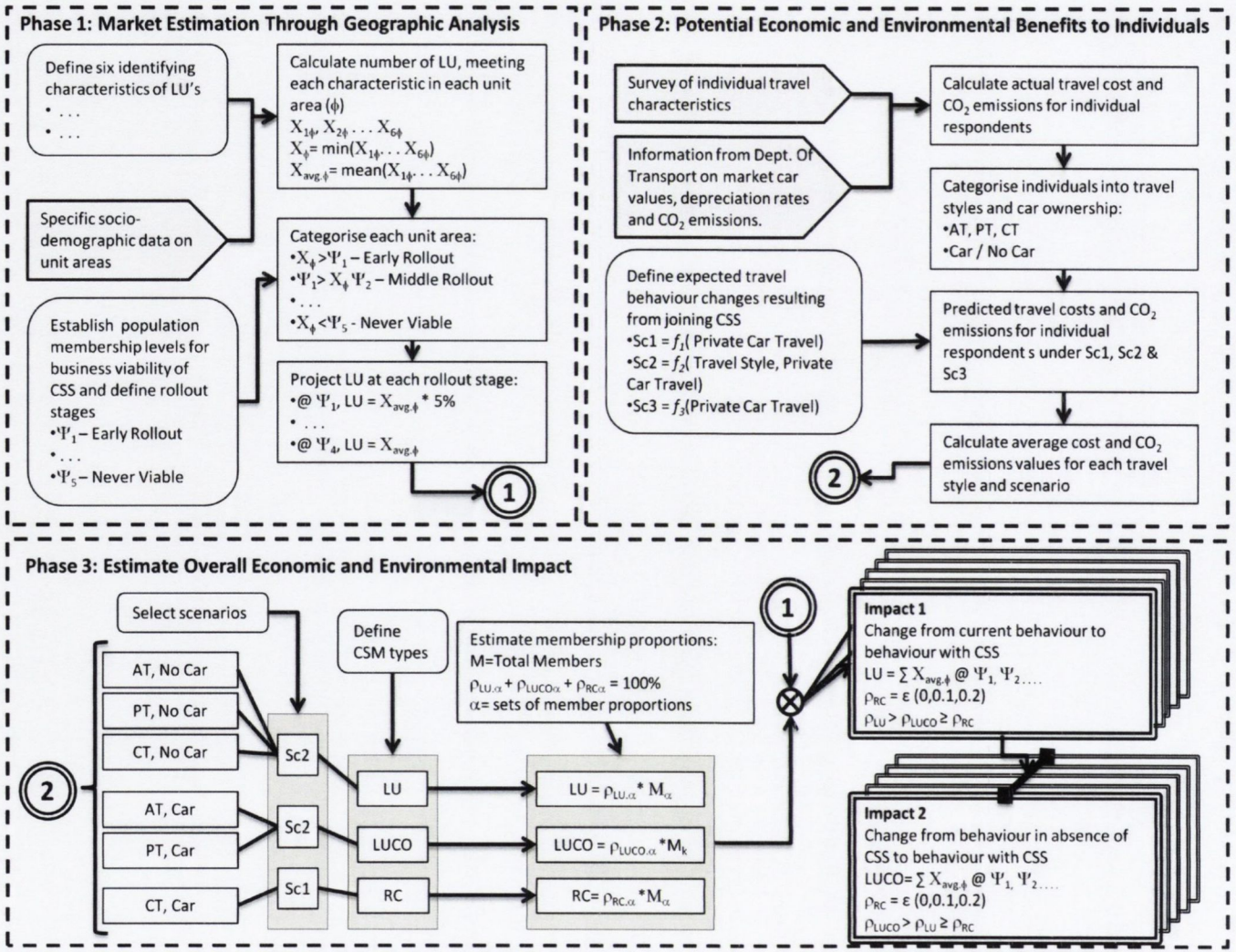

Figure 5.1: Methodology used to The Feasibility and Potential Benefits of Organised Car Sharing in Ireland

5.2 Methodology to Estimate the Potential Market of CSS

In this section we describe the methodology developed to estimate the potential market of CSS in Ireland. The methodology follows a three stage process.

In the first stage, a geographic analysis was carried out. Based on the population density of individuals likely to join car sharing and the business requirements of a CSS, each part of Ireland is categorised into one of five CSS viability levels. In the second stage an economic and environmental analysis was carried out to establish whether individual car owners could derive a financial benefit from a switch to car sharing, whether individual non-car owners could derive a benefit from car access at a reasonable price and whether there could be an environmental benefit arising from this behaviour change. The approach uses a best case, worst case and most likely scenario of travel behaviour change to calculate individual cost and CO_2 emissions impacts of joining a CSS. In the final stage, the results of the geographic and environmental analyses were combined to produce a model with the potential scale (total possible number of members in the state) and impact (reduction in CO_2 emissions) of differing levels of CS uptake. Figure 5.1 provides an overview of the full methodology, which is described in detail in Section 5.2.1, Section 5.2.3 and Section 5.2.4 below.

5.2.1 Market Estimation through Geographic Analysis

Based on the existing literature, this market estimation identifies the people most likely to join a CSS. It then considers the membership numbers required to establish a viable CSS. Together with socio-demographic data, these numbers are used to identify areas within Ireland where CSS is viable.

Likely Users

A number of researchers have investigated the personal characteristics and lifestyles of those who participate in car sharing. This literature was described fully in Section 2.2. The results of this research indicate that CS is most suitable for the lifestyles and travel patterns of people with certain characteristics and travel patterns; in short some individuals are more likely to join a CSS than others.

Following the literature described in Section 2.2, (Cervero, 2003; Loose, 2010; Martin & Shaheen, 2010; Steininger et al., 1996), six characteristics were selected to identify the most likely users of a CSS. These are numbered ($X_1 \ldots X_6$) and described as follows:

- X_1: Adult residents of 1-2 person households,

- X_2: Age between 25 - 49 years,
- X_3: Working or self-employed,
- X_4: Education qualification includes at least an ordinary degree,
- X_5: Adult residents of no car households,
- X_6: Adults who travel to work using modes other than driving.

Though the research indicates that these personal characteristics are common in members of a CSS, it should be noted that while each one of these traits is individually applicable to the majority of members in a typical CSS, the research does not provide a breakdown of how these traits overlap. In general an individual Car Sharing Member (CSM) is likely to possess only some of these traits, and some CSM will fall outside the Likely User (LU) categories and possess none of them. A seventh limiting criteria (X_7) is also calculated, that is the density of the adult population in each unit area.

As discussed in Chapter 1, the study area is primarily the county of Dublin, with an extended study area of Ireland. The SAPS dataset, derived from Census 2011 (CSO, 2012b) provides socio-demographic information on the population of Ireland (including Dublin) at the level of small areas, units of approximately 200 households. Specifically the SAPS dataset provides information on each Small Area's household size, age profile, the economic status of residents, the educational qualifications of residents, car ownership levels, and residents' means of travel to work and college. This dataset was described in greater detail in Section 3.2.1. The dataset was also used to calculate some of the summary statistics on transport in Dublin presented in Section 3.3.

Table 5.1: SAPS Dataset Columns Used And Calculations Carried Out To Identify Likely Users In Each Small Area.

Feature	Relevant Table and Field Names within SAPS Tables	Formula
X_1: Adult Residents of 1-2 Person Households	Theme 5 Private Households Table 2: Private households by size T5_2_1PH (1 Person Households (No of households)) T5_2_2PH (2 Person Households (No of households))	(T5_2_1PH + T5_2_2PH)*1.1/Area of the SA *Note: While the number of residents in 1 and 2 person households is given directly in T5_2_1PP and T5_2_2PP, these may include children. Loose (2010) found that each CS household had an average of 1.1 CS members. Therefore the household figures are used with a correction factor of 1.1*
X_2: Age between 25 - 49 years	Theme 1 Sex, Age and Marital Status Table 1: Population aged 0-19 by sex and year of age, persons aged 20+ by sex and age group T1_1AGE25_29T T1_1AGE30_34T T1_1AGE35_39T T1_1AGE40_44T T1_1AGE45_49T	(T1_1AGE25_29T + T1_1AGE30_34T + T1_1AGE35_39T + T1_1AGE40_44T + T1_1AGE45_49T)/Area of the SA
X_3: Working or Self Employed	Theme 8 Principal Status Table 1: Population aged 15 years and over by principal economic status and sex T8_1_WT (At Work (Total))	T8_1_WT/Area of the SA
X_4: Education Qualification includes at least an ordinary degree	Theme 10 Education Table 4: Population aged 15 years and over by sex and highest level of education completed T10_4_ODNDT (Ordinary Bachelor Degree or National Diploma (Total)) T10_4_HDPQT (Honours Bachelor Degree, Professional Qualification or both (Total)) T10_4_PDT (Postgraduate Diploma or Degree (Total)) T10_4_DT (Doctorate(Ph.D) or higher (Total))	(T10_4_ODNDT +T10_4_HDPQT +T10_4_PDT +T10_4_DT)/Area of the SA

Table 4.1 Contd.

Feature	Relevant Table and Field Names within SAPS Tables	Formula
X_5: Adult Residents of No Car Households	Theme 15 PC and Internet Access Table 1: Number of Households with Cars T15_1_NC (No motor Car)	(T15_1_NC*1.1)/Area of the SA *Note: The actual number of no car households is known, but the number of residents of no car households is not. Loose (2010) found that each CS household had an average of 1.1 CS members. 1.1 is therefore used as a correction factor.*
X_6: Adults who travel to work using modes other than driving	Theme 8 Principal Status Table 1: Population aged 15 years and over by principal economic status and sex T8_1_WT (At Work (Total)) Theme 11 Commuting Table 1: Population aged 5 years and over by means of travel to work, school or college T11_1_CD (Car Driver)	(T8_1_WT - T11_1_CD)/ Area of the SA *Note: This formula assumes that no students drive to school or college.*
Adult Density	Table 1: Population aged 0-19 by sex and year of age, persons aged 20+ by sex and age group T1_1AGE20_24T T1_1AGE25_29T T1_1AGE30_34T T1_1AGE35_39T T1_1AGE40_44T T1_1AGE45_49T T1_1AGE50_54T T1_1AGE55_59T T1_1AGE60_64T T1_1AGE65_69T T1_1AGE70_74T T1_1AGE75_79T T1_1AGE80_84T T1_1AGEGE_85T	(T1_1AGE20_24T+ T1_1AGE25_29T+ T1_1AGE30_34T+ T1_1AGE35_39T+ T1_1AGE40_44T+ T1_1AGE45_49T+ T1_1AGE50_54T+ T1_1AGE55_59T+ T1_1AGE60_64T+ T1_1AGE65_69T+ T1_1AGE70_74T+T1_1AGE75_79T+ T1_1AGE80_84T+ T1_1AGEGE_85T) / Area of the SA

Population per km^2 figures, derived from the SAPS dataset, were therefore used to calculate the number and density of people meeting each of the six LU characteristics in each unit area (ϕ): $(X_{1\phi}, X_{2\phi} \ldots X_{6\phi})$.

Business Requirements of CSS

CSS's operate by providing stations with one or more vehicles in locations convenient to their members. The provision and distribution of stations and vehicles must balance the competing

requirements of the members and the CSS. Together the research on CSMs and CSS provides a picture of how such services operate.

To maintain and profit from each car at a CS station, the CSS must have a certain number of members with a certain usage level within the accessible distance. If members use the service frequently, then to ensure availability the CSS must provide a higher number of cars per member and/or structure their pricing plans to encourage members to switch their reservations to off-peak rental periods. The number of CSMs per car sharing vehicle varies between 19-65 with an average of 32 in Europe and 38 in North America (Loose, 2010; Martin & Shaheen, 2010). It is not expected that LU will be the only members of the CSS, however they will provide the core membership enabling the CSS to reach a break-even point. From the literature between 60% and 90% of members will possess each LU characteristic. Based on this Table 5.2 below illustrates the range of likely user numbers needed to meet target CSM/vehicle targets at different percentage levels of LUs.

Table 5.2: Target LU Membership for Different LU Proportions and CSM/Vehicle Requirements

CSM/ Vehicle	Proportion LU			
	60%	70%	80%	90%
19	11	13	15	17
32	19	22	26	29
38	23	27	30	34
65	39	46	52	59

In areas of high demand, additional capacity may be provided by adding new CS stations, or by adding more cars to existing stations. To the CSS each station is an additional cost sink, to which staff must pay maintenance visits, and for which they may have to pay parking. Fewer stations will reduce overhead costs and increase profits. Loose (2010) found a European average of 1.92 cars per CS station. However, the CSS must balance this against CSMs wish to access cars at locations as convenient as possible to their home. Customer surveys in Europe indicate that a walking distance of up to 500m from the station is ideal. Beyond 700-800m customer take up is markedly reduced (Loose, 2010). Population densities per km^2 (radius = 564m), are therefore used as the basis of this analysis.

In summary, the number of members per car-sharing vehicle and car sharing station is location specific. It depends on the operating costs of specific car sharing locations, the pricing structure of the service and the level of demand from members. While this is the case, the narrow range of CSM/vehicle in Europe and North America suggests that CSS are typically viable in the range of 30-40 CSM/vehicle.

Viability Levels

In introducing the CSS to a new region, in this case study Ireland, a gradual build up of the service is anticipated, starting with the areas in which success is most likely and subsequently expanding (rolling out) to areas with less suitable populations. In the early stages of this rollout, a small proportion of the population with suitable lifestyles participates in the service. As the service gains credibility and capacity a higher proportion of the suitable population becomes members. The geographic analysis of the market was therefore performed by assuming multiple rollout phases. Based on the average number of members per vehicle described in this section and the vehicle/CSM estimates described in Table 5.2, a membership level of 25LU/Vehicle is chosen as the basis for this analysis.

To ensure a conservative categorisation the rollout areas were based on minimum LU, i.e. X_ϕ = min($X_{1\phi}$, $X_{2\phi}$ . . . $X_{6\phi}$), and the early and middle rollout stages assume 2 vehicles at each CS station. This condition is relaxed in the late rollout phase and 1 vehicle per CS station is estimated.

Accordingly, all the small areas in the Republic of Ireland were sub-divided into five groups on the basis of the viability of introduction of CSS in the area:

1. Early Rollout Areas (Ψ_1): Areas most suitable for CSS with X_ϕ = 1000 LU/km^2 and 50 of them (5%) were projected to join the CSS.
2. Middle Rollout Areas (Ψ_2): Areas suitable for CSS with additional policy and investment support with X_ϕ = 100 LU/km^2 and 50 of them (50%) were projected to join CSS.
3. Late Rollout Areas (Ψ_3): Areas suitable for CSS with a significant amount of policy and investment support with X_ϕ = 25 LU/km^2 and all (100%) were projected to join the CSS.
4. Maximum Limit Areas (Ψ_4): Areas with population density of 25 adults/km^2, but has fewer LU than late rollout areas. Private car ownership would require restrictions for CS to operate in these areas.

5. Never Viable Areas (Ψ_5): Areas with insufficient population density (i.e. <25 adults/km^2) to support CSS.

Calculation Procedure

The procedure for assigning each SA to a Rollout Phase is described in detail below:

1) As described in Table 5.1, seven densities for each of the 18,488 small areas were calculated. ($X_{1\phi}$, $X_{2\phi}$, $X_{3\phi}$, $X_{4\phi}$, $X_{5\phi}$, $X_{6\phi}$, Adult Density)
2) The adult density of each SA was then examined, and in cases where the SA had fewer than 25 Adults per km^2, the SA was assigned the Ψ_5 "Never Viable" label.
3) For each SA, the minimum of the six LU variables (X_ϕ) was then identified.
4) The formula shown in Equation 5.1 was then used to assign each remaining SA (ϕ) to the appropriate rollout stage. ($\Psi_1 - \Psi_4$)

Equation 5.1: Formula used to assign each SA to the appropriate rollout stage

$$\begin{aligned} X_\phi > 1000 &\xrightarrow{assign} \Psi_1 \\ X_\phi > 100 &\xrightarrow{assign} \Psi_2 \\ X_\phi > 25 &\xrightarrow{assign} \Psi_3 \\ X_\phi \leq 25 &\xrightarrow{assign} \Psi_4 \end{aligned} \qquad (5.1)$$

5.2.2 Potential Economic and Environmental Benefits to Individuals

Having assigned a rollout stage to each small area, the analysis then proceeds to its second phase. This phase analyses whether, at the micro-level, CSS is a viable proposition which offers measurable benefits to the individuals who become members. The potential benefits examined are reduced transport costs and reduced CO_2 emissions. The model therefore calculates the financial and environmental benefits that accrue to individuals who join a CSS.

A four step analysis was therefore carried out. In the first step a travel and activity survey was developed and implemented. This survey's development and distribution is described in detail in Sections 3.4. The second step calculates each respondent's individual travel CO_2 emissions and cost of transport. This step uses information provided by respondents to the survey described in Chapter 3 in conjunction with Department of Transport data on CO_2 emissions. The CO_2 emissions

and cost of transport calculations undertaken are described in detail in Section 4.2 and Section 4.3.

In the third step, the sample of interest from the survey responses was extracted and individuals were categorised into one of three travel style groups. In the final step, three behavioural change scenarios were developed and applied to responses of individuals in each of the travel style groups. The rest of this section now describes the third and fourth steps in the analysis of economic and environmental benefits.

Division into Travel Style Groups

From the results of the survey, the sample of interest to this phase of analysis was extracted and these respondents were divided into travel style groups which were used as a basis to model behavioural change.

The criteria used to select the sample of interest were based on the results of the geographic analysis described in section 5.2.1. The geographic analysis confirmed that a CSS service can only operate in urban areas with a relatively high population density. As Dublin is the largest urban area within the study area, Dublin residents were chosen as having travel patterns most likely to be similar to the travel patterns of those living in areas where a CSS operates. Due to the distribution methods used, the survey garnered a large number of responses from students. The literature described in Section 2.2 confirms that, unless specifically targeted students are unlikely to become CSM and that among those who are already CSM, a large majority are employed therefore employed respondents were selected. In summary, the limits used were that respondents must be Dublin residents who presented "*Working for Payment or Profit*" as their principal occupation.

In identifying travel style groups, the aim was to group respondents with similar travel characteristics. These groupings are then used to describe the impacts of becoming a CSM on the CO_2 emissions and costs of travel of individual respondents. On inspection of the processed survey responses, a respondent's CO_2 emissions and costs were closely related to the modes of travel they used most frequently and their ownership of a car. Respondents were therefore classified into three 'travel style' categories based on their dominant modes of travel. These were: 1) *Active Traveller* (AT) who took most trips by walking or cycling, 2) *Public Transport Traveller* (PT) where the respondent mostly used bus/tram/train and 3) *Car Traveller (CT)* where most trips were made on private car as either driver or passenger. The dominant travel style category (TS) was determined by:

Equation 5.2: Travel Style Category Assignment for an Individual Respondent

$$TS = \begin{cases} TS_T, T_1 > 1.25 * T_2 \\ TS_D, T_1 \leq 1.25 * T_2 \end{cases} \quad (5.2)$$

where TS_T is the travel category on which a respondent made the greatest number of journeys, T_1 is the number of journeys made using the mode(s) specific to that travel category, T_2 is the number of journeys made using the mode(s) specific to the travel category on which a respondent made the second greatest number of journeys and TS_D is the travel category on which a respondent travelled the greatest distance. The travel modes considered were active (walking and cycling), public transport (bus, train, tram) and cars (private car). Each travel style group was then further sub-divided according to a respondent's car ownership status. Summary statistics for each travel style are presented in Table 5.3.

Table 5.3: Summary of Survey Data Used for Car Sharing Analysis

	Active Traveller		Car Traveller		Public Transport Traveller		All Respondents
	Non-car Owner	Car Owner	Non-car Owner	Car Owner	Non-car Owner	Car Owner	
Number of Respondents	189	122	45	248	123	89	816
% of Total	*23.16%*	*14.95%*	*5.51%*	*30.39%*	*15.07%*	*10.91%*	*100.0%*
% Female	*47.6%*	*47.5%*	*57.8%*	*57.7%*	*52.8%*	*58.4%*	*53.2%*
Personal Characteristics							
Average Age	33.0	37.6	32.4	37.5	32.7	37.9	35.5
Average Household Size	2.20	2.55	2.64	2.57	2.39	2.54	2.54
Travel Characteristics							
Average Km/Year	7813	8164	12809	14232	7139	10057	10235
Average No. of Trips/Yr	986	944	900	1070	933	1008	995
Average Travel Time (Hrs)	366.1	336.3	348.3	391.5	387.8	458.6	381.7
Average Annual Travel Cost	€1,108	€3,750	€2,570	€5,559	€1,784	€5,256	€3,491
Average CO_2 Emissions(kg/yr)	283.2	496.5	1006.4	1457.8	448.9	731.3	785.8

Behaviour Change Scenarios

It is expected that the likely environmental and economic impacts of joining CSS can be analysed appropriately by establishing an upper limit, a lower limit and a most likely scenario. Accordingly, a scenario based approach was used to model the behavioural changes that can be expected in

individuals on joining car sharing. The behavioural changes were assumed based on information from existing literature (Martin & Shaheen, 2010). In the study in North America, it was recorded that across 11 CS organisations, over 50% of the 6,281 CSMs reported driving fewer than 1,200km per annum in CS vehicles, which was on average less than 9% of the driving distance covered by members in private ownership vehicles which were sold as a result of joining CSS.

Assuming similar behavioural changes, three hypothetical scenarios were designed to estimate the economic and environmental impacts of switching to CSS for the survey respondents. The calculations for each scenario are based on the answers provided by respondents to the survey and the rates charged by GoCar, the only CSS operating in Ireland, in the February/March 2012 period, i.e. during the time frame in which the survey was conducted. Table 5.4 below describes the variables used in the calculations for the various scenarios. Further discussion of the scenario's and the methodology used to develop each scenario is then provided.

Table 5.4: Variables and Formulas Used to Describe Behaviour Change Scenarios

Name (Variable)	Based On	Formula
Monthly Fee (MF) *Monthly fee charged by CSS to CSM.*	Go Car Rates February/March 2012 (GoCar.ie, 2012) Predicted rate of CSS usage per scenario.	€15/month if predicted travel greater than 100km/month €10/month if predicted travel greater than 25km/month and less than 100km/month €5/month if predicted travel greater than 0km/month and less than 25km/month €0/month if no predicted travel
Hire Cost (HC) *Cost per Hour for bookings to CSS cars.*	Go Car Rates February/March 2012 (GoCar.ie, 2012) Predicted rate of CSS usage per scenario	€4.75/hour if predicted travel greater than 100km/month €5.25/hour if predicted travel greater than 25km/month and less than 100km/month €5.75/hour if predicted travel less than 25km/month
Km Cost (KMC_{CS}) *Cost per km travelled in CSS cars.*	Go Car Rates February/March 2012 (GoCar.ie, 2012) Predicted rate of CSS usage per scenario.	€0.45/km in all cases. **Table 5.4 Contd.**
Travel Time per Car Journey (TTCJ)	Reported number of journeys undertaken in cars and reported time	Number of journeys made in cars/time spent travelling in cars: $TTCJ=PC_{jour}/PC_{time}$

Name (Variable)	Based On	Formula
Average travel time/car journey (min)	spent travelling in cars by respondents. Journeys reported by survey respondents are modified per scenario description	Where: PC_{jour}: Annual distance in km travelled in private vehicles by the respondent PC_{time}: Annual time in minutes spent in private vehicles by the respondent
Booking Length (BL) *The booking length (hours) the CSM must make in order to make an average journey.*	The TTCJ calculated above, plus an allowance of an additional ten minutes booking time per journey, and rounded up to the nearest half hour.	BL = (ROUNDUP((TTCJ+10)*2/60,0)/2
CSS CO_2 *CO_2 emissions resulting from travel in CS vehicles*	Two figures are used. 150gCO_2/km is based on a conservative estimate of the CO_2 emissions of a standard car being used as a car sharing vehicle. 0gCO_2/km is based on an optimistic estimate if electric vehicles, powered using excess electricity are used.	If Conventional Vehicles - 150gCO_2/km or If Electric Vehicles - 0gCO_2/km

Scenario 1 (Sc1)

This scenario can be considered as the best case scenario, and it is specified with a view to causing the maximum likely decrease in CO_2 emissions. In this scenario, everyone joins CSS. The research shows that on joining CS, a significant number of new members greatly decrease their travel in cars. The research by Loose (2010) and Martin and Shaheen (2010) indicates that after joining CS, their travel in cars is about 10% of what it was previously. The question then arises of what happens to the remaining 90% of travel. A number of possible scenarios exist for how CSM replace their car journeys with travel in other modes. For instance, the journeys may simply not be made; trips may be combined more efficiently and made in a single trip in a CS vehicle instead of in multiple journeys over the course of a month or year, or journeys may be made using alternate modes of transport.

For consistency and convenience, it was assumed that the remaining 90% of new CSM's travel distance is covered in alternatives modes of travel such as public transport or active modes at a cost similar to their existing costs for these modes of transport and in a ratio similar to the ratio they already use. A respondent's reported annual a) distance travelled in a private car, b) journeys made in a private car and c) time spent in a private car is first calculated and labelled PC_{dist}, PC_{jour} and PC_{time} respectively.

Under the scenario, respondent's make 10% of these journeys (PC_{jour}) in a CS vehicle. The three variables are used with the calculations and variables outlines in Table 5.4 above to calculate an appropriate cost and CO_2 impact for each respondent. The remaining 90% of journey distance travelled is then distributed among active and public modes of transport. For each respondent, the full calculation is undertaken as follows:

1. Calculate the distance travelled in CS vehicles (10% *PC_{dist}) and identify the appropriate monthly fee (MF) and CS vehicle hire cost (HC) for the respondent.
2. Using PC_{jour} and PC_{time}, calculate a TTCJ and BL for the respondent.
3. The total cost of travel in CS vehicles under Scenario 1 for the respondent is then calculated as the sum of the monthly fees, hourly fees and distance fees. This is described in Equation 5.3 below.

Equation 5.3: Respondent's Annual Cost of CS Vehicle Use Under Scenario 1

$$Cost = MF * 12 + (HC * BL * PC_{jour} + PC_{dist} * KMC_{CS}) * 10\% \quad (5.3)$$

4. The CO_2 emissions of this travel in CS vehicles are then calculated based on the type of vehicle (conventional or electric) that is under consideration. The equations used to calculate this are provided in Equation 5.4 below.

Equation 5.4: Respondent's Annual CO2 emissions from travel in CS Vehicles under Scenario 1 for (a) Conventional and (b) Electric vehicles

(a) $Conventional = 150 * PC_{dist} * 10\%$ 5.4 (a)

(b) $Electric = 0 * PC_{dist} * 10\% = 0$ 5.4 (b)

5. Based on the respondent's survey data, the proportion of non-private vehicle distance travelled by the respondent on (a) Bus, (b) Train, (c) Bus and Train together and and (d) Active Modes is calculated. These are labelled ρ_{Bus}, ρ_{Train} ,ρ_{PT} and ρ_{ACT} respectively. Where no travel is reported on any of these modes, a default assumption of 25% Bus, 25% Train, 50% Active Travel is assumed.

6. Based on the respondent's survey data, a cost/km for their travel on public transport is calculated. (KMC_{PT}) As bus and train travel can be undertaken on the same ticket, a single KMC_{PT} value for both Bus and Train costs is used. Where no travel takes place or no costs are reported an average value of 13.1c/km is assigned. This 13.1c/km is based on the average reported cost for all respondents to the survey. Walking and cycling are assumed to attract no additional cost. The cost of the additional travel on public and active modes is then calculated following Equation 5.5.

Equation 5.5: Respondent's Additional Annual Spending on Public Transport under Scenario 1.

$$Cost = 90\% * PC_{dist} * \rho_{PT} * KMC_{PT} \quad (5.5)$$

7. The CO_2 impact of additional travel on public and active modes is then calculated using ρ_{Bus}, ρ_{Train} and the emission figures described in Section 4.3. The formula used is described in Equation 5.6 below:

Equation 5.6: Respondent's additional CO_2 from Travel on Public Transport under Scenario 1

$$CO_2 = 90\% * PC_{dist} * \rho_{Bus} * CO_2(Bus) + 90\% * PC_{dist} * \rho_{Train} * CO_2(Train) \quad (5.6)$$

8. The final calculations are then made by removing any costs and CO_2 emissions attributed to the respondent's travel in Private Cars from the Respondent's totals. The additional impacts calculated in Equations 5.3, 5.4, 5.5 and 5.6 are then added as appropriate.

Scenario 2 (Sc2)

This scenario represents the most likely behavioural changes among CS members. In this scenario respondents are divided into three categories based on their travel style groupings. These categories are (a) car owners with a car travel style, (b) car owners with an active or public transport travel style and (c) non-car owners.

It is assumed that those in category (a) do not join the CSS, and consequently make no changes to their travel patterns. Those in category (b) join the CSS and follow Scenario 1, i.e. 10% of their reported journey distance travelled in a private car is covered in a CS cars and the remaining 90% of reported journey distance is made using alternative modes. The methodology for calculating the impact of their behaviour change follows that described under Scenario 1.

Those in category (c) do join the CSS and their behavioural change is modelled as replacing all of their current car trips with CS trips subject to a minimum of 130km/year. This is intended to

mimic the category of CSM, identified by Martin and Shaheen. (2010), who increase their usage of cars upon joining the CSS. The 130km/year average distance is estimated based on the average CS usage of GoCar members in Dublin (GoCar.ie, 2013). The methodology follows that described under Scenario 1, except that where the value of 10% of car journeys is used, this is replaced with 100%. Consequently no calculations are made using Equation 5.5 or 5.6, as no additional travel on public transport is expected.

Scenario 3 (Sc3)

This scenario represents a worst case scenario in which minimal behavioural change occurs among CS members. All members replace their current levels of car travel exactly with travel as the sole occupant of a CS vehicle. The methodology otherwise follows that described under Scenario 1. Costs incurred when travelling in CS vehicles are calculated using Equation 5.3 and Equation 5.4, using PC_{dist} instead of 10% PC_{dist} as the basis for the calculation. No additional distance is travelled via public or active transport, therefore Equation 5.5 and Equation 5.6 are not used.

5.2.3 Estimate Overall Economic and Environmental Impact

This analysis aims to establish the total economic and environmental impact if CS is adopted more widely in Ireland. The individual impacts as calculated following the methodology described in section 5.2.2 were projected onto each small area of the country using the rollout stages described in section 5.2.1.

The determinants of the impact are the levels of uptake of CSS and the travel behaviour change of those who join the CSS. Based on existing research (Loose, 2010; Martin & Shaheen, 2010), 3 member types are considered, i.e. LU, Low Usage Car Owners (LUCO) and those making a Radical Change (RC). The proportions in each member type depend on the exact characteristics of the CSS, government policy, population profile in the target areas etc. A range of estimates regarding membership levels and consequent impacts were therefore calculated.

It is expected that between 60% - 90% of CSM will be from the LU demographic (Loose, 2010; Martin & Shaheen, 2010). These LU correspond to those with AT, PT and CT styles who do not own a car and who join the CSS to gain access to a car. The remaining 10% - 40% of users are comprised of LUCO and RC. The LUCOs correspond to the AT and PT who own a car, described in Section 5.2.2. Members of this group tend to sell their cars after joining CSS. The RC group are

environmentally aware CT who own a car and who radically change their travel behaviour on joining CSS. Membership numbers were calculated as follows:

Equation 5.7: Membership Numbers Calculation

(a) $$M_{\alpha} = \frac{LU}{\rho_{LU.\alpha}} = \frac{LUCO}{\rho_{LUCO.\alpha}} = \frac{RC}{\rho_{RC.\alpha}} \qquad 5.7\ (a)$$

(b) $$\rho_{LU.\alpha} + \rho_{LUCO.\alpha} + \rho_{RC.\alpha} = 100\% \qquad 5.7\ (b)$$

where M_{α} is the total number of members, ρ_{LU}, ρ_{LUCO}, ρ_{RC}, are the proportion of members who are LU, LUCO and RC respectively. The subscript α indicates the set of user proportions under consideration. The overall impact was then calculated in two ways which differ in the way they consider the changes in travel behaviour.

Impact 1: Immediate Impact

This is the case of immediate impact which is directly measurable. The travel behaviour changes that are considered here include non-car owner LU members increasing their car trips due to additional vehicle access on joining CSS and car-owners (LUCO and RC) driving less and selling their car. In immediate impact, reasonable travel behaviour change is modelled by assuming a CSM group with the largest share of LU, moderate numbers of LUCO and very few RC type members. This is similar to the scenario described as 'observed impact' by Martin and Shaheen (2010). Membership numbers are calculated using Equation 5.7 and assuming LU = $\sum X_{avg\phi}$ at the appropriate rollout stage, where $X_{avg\phi}$ is the mean value of $(X_{1\phi} \ldots X_{6\phi})$ for unit area ϕ.

Impact 2: Ideal Impact

This is a more idealistic scenario and can be termed as ideal impact. The immediate impact calculated the reduction in travel costs and CO_2 emissions based on changes to current travel behaviour; however this may not present an accurate picture of the potential benefits of introducing CSS.

The ideal impact takes into account the absence of possible changes that could have happened if CSS was not available. This is similar to the scenario described as 'full impact' by Martin and Shaheen (2010), i.e. this scenario considers how travel behaviour would change if CSS was not available. While the majority of CS members may not own a car at the point of joining a CSS, it is likely that a certain percentage would have purchased a car in the absence of CS availability. The benefits of joining CSS are therefore more accurately represented by applying the change in travel

patterns to non-car owners who could have become car owners in the absence CSS. The impact CSS is therefore better represented by modelling a higher proportion of new members as LUCO and fewer members as LU. The ideal impact realises the maximum environmental benefits of introducing CSS. Membership numbers are calculated using Equation 5.7 and assuming LUCO = $\sum X_{avg\phi}$ at the appropriate rollout stage.

5.3 Results of CSS Feasibility Analysis

In this section the results of the analyses carried out following the methodology described in Section 5.2 is provided.

5.3.1 Market Estimation Through Geographic Analysis

The 2011 Irish census data was used to identify areas suitable for establishing car sharing stations with sufficient densities of probable CSM. The entire country was divided into areas more and less suitable for car sharing, based on the number of potential members in each area. The results are provided in Table 5.5, Figure 5.2 & Figure 5.3.

Table 5.5: Projected Likely User membership of Car Sharing Service

	No. of Small Areas	% of Total Land Area	Total Population	Adult Population	Estimated Total LU	Projected LU as CSM	Projected LU as CSM as % of Adult Population
Ireland							
Early Roll Out	1,093	0.0%	223,663	189,990	85,962	4,298	0.1%
Middle Roll Out	7,150	0.6%	1,733,223	1,309,339	490,611	245,306	7.4%
Late Roll Out	9,999	1.3%	2,477,227	1,835,865	679,289	679,289	20.4%
Maximum Limit	14,436	19.4%	3,637,354	2,649,730	964,951	964,951	29.0%
Never Viable	*4,052*	*80.6%*	*950,898*	*675,913*			
Dublin City and County							
Early Roll Out	923	1.8%	193,331	163,675	74,815	3,741	0.4%
Middle Roll Out	3,744	17.7%	948,649	722,253	279,813	139,906	14.7%
Late Roll Out	4,449	27.1%	1,159,237	871,867	332,910	332,910	34.9%
Maximum Limit	4,795	82.3%	1,269,145	949,728	360,121	360,121	37.8%
Never Viable	*11*	*17.7%*	*3,924*	*2,867*			
Cork City							
Early Roll Out	85	4.4%	15,159	13,373	5,692	285	0.3%
Middle Roll Out	414	50.7%	91,308	73,557	26,184	13,092	13.9%
Late Roll Out	499	82.6%	114,443	90,766	31,713	31,713	33.7%
Maximum Limit	519	100.0%	119,230	94,079	32,761	32,761	34.8%
Never Viable	*0*	*0.0%*	*0*	*0*			
Limerick City							
Early Roll Out	17	1.0%	3,710	3,103	1,279	64	0.1%
Middle Roll Out	166	28.7%	36,275	28,137	9,731	4,866	11.4%
Late Roll Out	226	58.2%	50,668	38,715	13,167	13,167	30.7%
Maximum Limit	258	100.0%	57,106	42,867	14,511	14,511	33.9%
Never Viable	*0*	*0.0%*	*0*	*0*			
Galway City							
Early Roll Out	25	1.0%	4,068	3,711	1,520	76	0.1%
Middle Roll Out	234	29.4%	56,679	44,175	16,269	8,135	14.0%
Late Roll Out	281	45.3%	68,768	53,166	19,694	19,694	33.9%
Maximum Limit	307	100.0%	75,529	58,083	21,511	21,511	37.0%
Never Viable	*0*	*0.0%*	*0*	*0*			

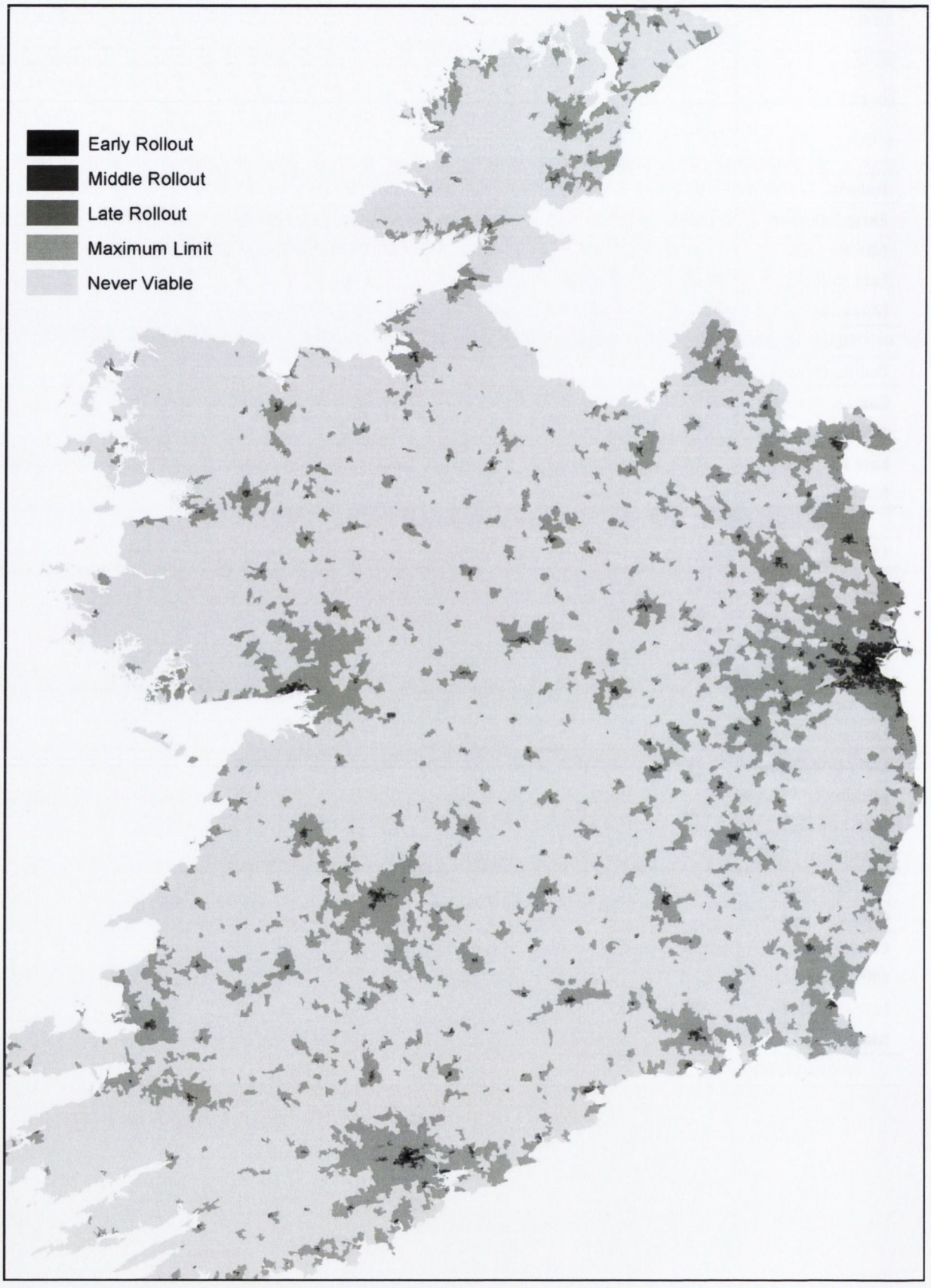

Figure 5.2: Car Sharing Potential, Ireland

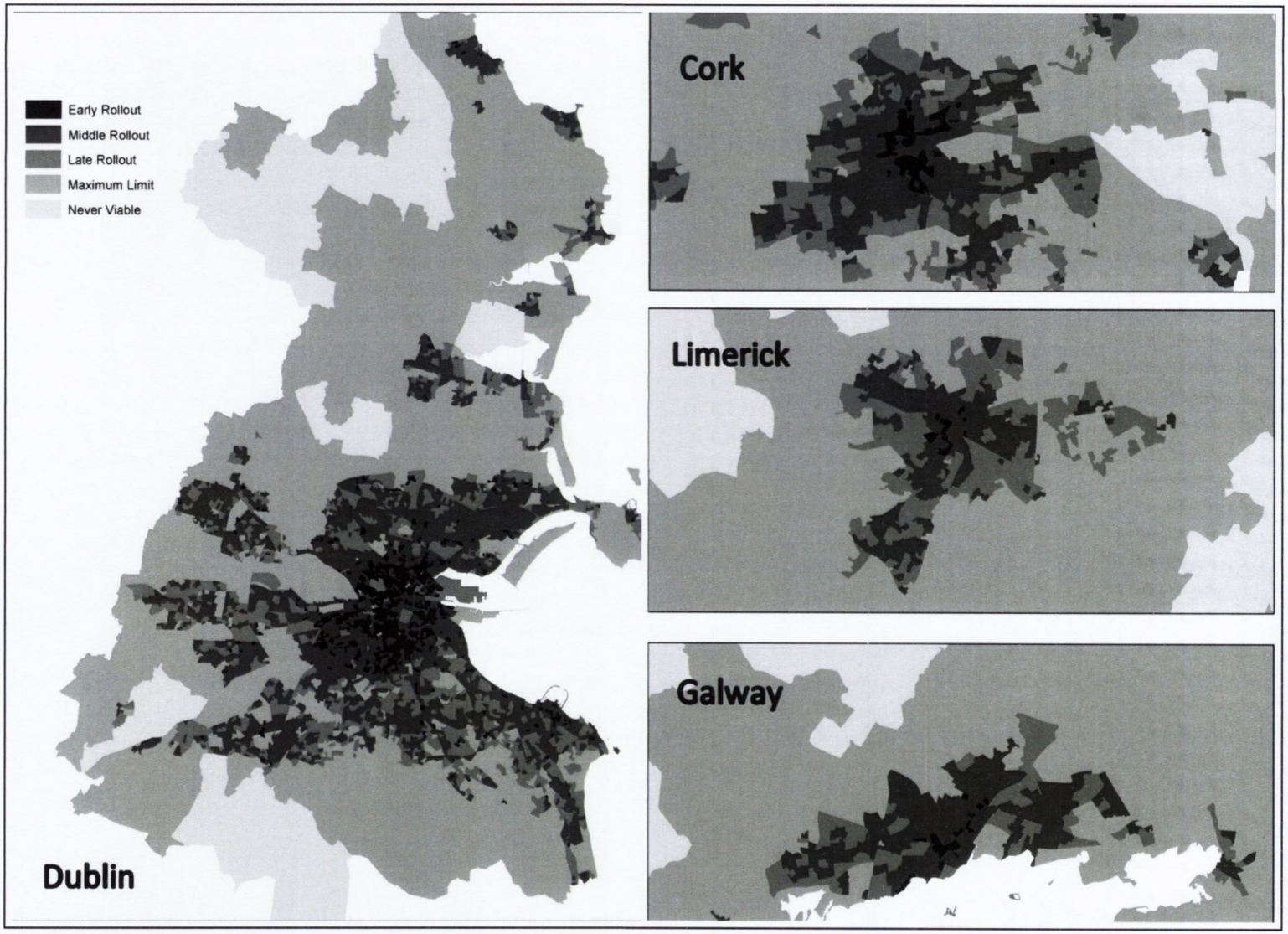

Figure 5.3: Car Sharing Potential, Dublin, Cork, Limerick, Galway

It can be observed that the population of LU is concentrated in areas with higher population densities, principally the four main cities: Dublin, Cork, Galway and Limerick. The four main cities together, account for 97% of the likely users in areas with the potential for early rollout of CS. In addition they account for 68% at middle rollout and 59% of the late rollout possibilities. In the early rollout stage, Dublin accounts for 87% of the expected LU, falling to 57% for middle rollout, and 49% for the late rollout stage. The Dublin area clearly has the most potential for the introduction of CS. The second largest city, Cork accounts for 7% of users at early rollout stage and 5% at both the middle and late rollout stages. For the entire country at the early rollout stage, 2.5% of the entire adult population were estimated as LU. In a late rollout, around 20% of the adult population can join CSS.

From Figure 5.2 & Figure 5.3, it is evident that outside the 4 main cities, many of the areas suitable for CS are discontinuous and may therefore be unsuitable for efficient management of a CSS, particularly in the initial stages when uptake is likely to be low. For the early and middle rollout stages Dublin County, including the administrative areas of Dublin City, Dun Laoghaire/Rathdown, Fingal and South Dublin is the only continuous area with a high density of suitable locations. Hence, in the later subsections the overall impact of introduction of CSS has been studied in further detail for Dublin County along with the entire country.

5.3.2 Potential Economic and Environmental Benefits to Individuals

This analysis was undertaken to establish whether CS presents financial and economic benefits to customers. The reported costs and emissions as calculated by the survey respondents are presented in Table 5.6 along with estimated costs and emissions if the respondents joined CSS. The estimated costs and emissions were calculated considering travel behaviour change as described in scenario 1 scenario 2 and scenario 3 in section 5.2.2. The results suggest that *active* and *public transport travellers* who own a car and sell their car to join CSS, save an average €3515 per annum (*active traveller* saves €3145 and *public transport traveller* saves €3818). In the best case scenario, where *car travellers* join CSS, they tend to make an even bigger saving than others. For non-car owners, *active* and *public transport travellers* joining CSS incurs additional costs. The projected additional cost to non-car owners is reasonable, particularly when compared to the alternative option of a car purchase.

The results for CO_2 emissions were very similar to the travel costs, i.e. car owner, *active* and *public transport travellers* can reduce their CO_2 emission significantly by joining CSS and for non-car

owners who use public and active transport, CS is likely to increase CO_2 emissions slightly. A further reduction in CO_2 emissions is possible if more energy efficient cars are deployed by CS companies.

Table 5.6: Individual Financial and Environmental Impacts of joining a Car Sharing Service

		Active Traveller		Car Traveller		Public Transport Traveller	
		Non-car Owner	Car Owner	Non-car Owner	Car Owner	Non-car Owner	Car Owner
Annual Travel Cost Estimation (Euros)							
Observed Cost		€1,108	€3,750	€2,570	€5,559	€1,784	€5,256
	Scenario 1 (best case)	€1,055	€965	€3,786	€3,261	€1,822	€2,115
	Scenario 2 (most probable)	€1,286	€965	€2,570	€5,559	€1,964	€2,115
	Scenario 3 (worst case)	€1,744	€3,111	€6,827	€8,827	€2,305	€3,633
Annual Travel Related CO_2 Emission Estimation (Kg/Yr)							
Observed Emission		283.2	496.5	1006.4	1457.8	448.9	731.3
Conventional cars	**Scenario 1 (best case)**	240.6	179.9	669.2	598.0	428.0	585.6
	Scenario 2 (most probable)	293.4	179.9	1006.4	1457.8	458.4	585.6
	Scenario 3 (worst case)	394.4	689.4	1560.2	1943.7	448.9	731.3
Electric cars	**Scenario 1 (best case)**	148.5	92.2	462.5	380.0	223.9	363.3
	Scenario 2 (most probable)	283.0	92.2	1006.4	1457.8	448.6	363.3
	Scenario 3 (worst case)	179.8	91.4	172.2	98.1	351.6	367.2

5.3.3 Overall Economic and Environmental Impacts

This section combines the previous analyses to produce an estimate of the overall impact of the introduction of CSS on a widespread basis to Ireland for the differing levels of uptake. The results for Dublin are presented in Table 5.7 and in Table 5.8 for Ireland.

In early rollout stages, the CSM in Dublin are responsible for a very large percentage of the total travel cost saving and total CO_2 reduction for Ireland. However, in later rollout stages, the rest of the country participates more in travel cost and CO_2 reduction. In this context, it is also important to remember around 28% of the total population is based in Dublin city and county.

Table 5.7: Membership Numbers, Environmental Impacts and Financial Savings of Car Sharing Rollout in Dublin

DUBLIN		Impact 1 (immediate)				Impact 2 (ideal)			
% of members per category	LU	70%	70%	60%	50%	20%	20%	30%	30%
	LUCO	30%	20%	30%	30%	80%	70%	60%	50%
	RC	0%	10%	10%	20%	0%	10%	10%	20%
Number of projected CSM	Early Roll Out	5,344	5,344	6,235	7,481	4,676	5,344	6,235	7,481
	Middle Roll Out	199,866	199,866	233,177	279,813	174,883	199,866	233,177	279,813
	Late Roll Out	475,586	475,586	554,850	665,820	416,137	475,586	554,850	665,820
	Maximum Limit	514,459	514,459	600,202	720,242	450,151	514,459	600,202	720,242
kt of CO_2 saved in Conventional Car CSS	Early Roll Out	0.4	0.7	1.0	1.8	0.9	1.4	1.4	2.2
	Middle Roll Out	13.4	25.7	35.9	67.4	33.9	51.1	53.7	81.6
	Late Roll Out	32.0	61.3	85.5	160.5	80.7	121.5	127.7	194.2
	Maximum Limit	34.6	66.3	92.5	173.6	87.3	131.4	138.1	210.0
kt of CO_2 saved in Electric Car CSS	Early Roll Out	0.5	0.9	1.2	2.2	1.1	1.7	1.8	2.7
	Middle Roll Out	18.1	32.9	45.4	83.7	42.0	62.9	66.4	100.5
	Late Roll Out	43.0	78.3	108.0	199.2	100.1	149.7	158.0	239.2
	Maximum Limit	46.5	84.7	116.9	215.4	108.2	162.0	170.9	258.7
Cost Saved by CSM (Million Euros)	Early Roll Out	€4.1	€3.8	€6.3	€9.4	€ 10.8	€ 12.0	€ 12.1	€ 14.1
	Middle Roll Out	€ 154.1	€ 141.4	€ 237.0	€ 353.1	€ 405.2	€ 450.3	€ 453.3	€ 526.1
	Late Roll Out	€ 366.7	€ 336.4	€ 564.0	€ 840.2	€ 964.2	€ 1,071.6	€ 1,078.7	€ 1,251.9
	Maximum Limit	€ 396.7	€ 363.9	€ 610.1	€ 908.8	€ 1,043.0	€ 1,159.2	€ 1,166.8	€ 1,354.2

Table 5.8: Membership Numbers, Environmental Impacts and Financial Savings of Car Sharing Rollout in Ireland

IRELAND		Impact 1 (immediate)				Impact 2 (ideal)			
% of members per category	LU	70%	70%	60%	50%	20%	20%	30%	30%
	LUCO	30%	20%	30%	30%	80%	70%	60%	50%
	RC	0%	10%	10%	20%	0%	10%	10%	20%
Number of projected CSM	Early Roll Out	6,140	6,140	7,164	8,596	5,373	6,140	7,164	8,596
	Middle Roll Out	350,437	350,437	408,843	490,611	306,632	350,437	408,843	490,611
	Late Roll Out	970,413	970,413	1,132,149	1,358,579	849,112	970,413	1,132,149	1,358,579
	Maximum Limit	1,378,502	1,378,502	1,608,252	1,929,903	1,206,189	1,378,502	1,608,252	1,929,903
kt of CO_2 saved in Conventional Car CSS	Early Roll Out	0.4	0.8	1.1	2.1	1.0	1.6	1.6	2.5
	Middle Roll Out	23.6	45.1	63.0	118.2	59.5	89.5	94.1	143.1
	Late Roll Out	65.3	125.0	174.5	327.4	164.6	247.9	260.5	396.2
	Maximum Limit	92.8	177.6	247.9	465.1	233.9	352.1	370.1	562.8
kt of CO_2 saved in Electric Car CSS	Early Roll Out	0.6	1.0	1.4	2.6	1.3	1.9	2.0	3.1
	Middle Roll Out	31.6	57.7	79.6	146.8	73.7	110.3	116.4	176.2
	Late Roll Out	87.6	159.8	220.5	406.4	204.2	305.5	322.4	488.0
	Maximum Limit	124.5	227.0	313.2	577.3	290.0	434.0	458.0	693.2
Cost Saved by CSM (Million Euros)	Early Roll Out	€4.7	€4.3	€7.3	€ 10.8	€ 12.4	€ 13.8	€ 13.9	€ 16.2
	Middle Roll Out	€ 270.2	€ 247.9	€ 415.6	€ 619.1	€ 710.5	€ 789.6	€ 794.8	€ 922.5
	Late Roll Out	€ 748.3	€ 686.3	€ 1,150.8	€ 1,714.3	€ 1,967.5	€ 2,186.6	€ 2,201.0	€ 2,554.4
	Maximum Limit	€ 1,063.0	€ 975.0	€ 1,634.7	€ 2,435.2	€ 2,794.8	€ 3,106.1	€ 3,126.5	€ 3,628.7

Impact 1: Immediate Impact

This scenario assumed very little change in travel behaviour. It is expected the non-car owner, LU, will form the largest share of CSM and the related economic and environmental impact was calculated by changing the percentage share of LU, LUCO and RC groups. In the 4 presented cases the LU share was varied between 50-70%, LUCO share was varied between 20-30% and RC between 0-20%. The trends are very similar for both the economic and the environmental impacts. A larger percentage of LUCO and RC members resulted in higher cost and CO_2 savings. In general, a greater change in travel behaviour by new CS members resulted in greater economic and environmental benefits being observed. Between LUCO & RC members, a higher percentage of LUCO members induced more costs savings and a higher percentage of RC members indicated higher environmental benefits.

The low projected usage of CS vehicles by LU and LUCO members resulted in little difference between the amount of CO_2 saved for electric and conventional cars. However, when a large percentage of RC population was assumed in the CSM group, the difference between the amount of CO_2 saved for electric and conventional cars was more pronounced due to their greater use of CS vehicles. Among the 4 cases discussed, with some policy support from government, the 60%LU/30%LUCO/10%RC spilt in the middle rollout areas in Dublin seem the most probable projection for introducing CSS. This would save 35.9kt of travel related CO_2 emissions.

Impact 2: Ideal Impact

The ideal impact takes into account the absence of possible changes that could have happened if CSS was not available. In the absence of a CSS, it is believed that a significant proportion of those currently in the LU category would become car owners, typically in the LUCO category. The ideal impact therefore models the impact of CS with a higher proportion of LUCO members.

Again, 4 cases are presented. In these, the LU share is varied between 20-30%, the LUCO share is varied between 50-80% and the RC share between 0-20%. As observed in the case of impact 1, the bigger changes in travel patterns reflected larger benefits. Therefore the number of RC members was the biggest factor in early rollout stages; this effect reduces in the later rollout stages. The higher number of LUCO members was the next bigger factor influencing benefits; between the 30%LU/60%LUCO/10%RC and 20%LU/70%LUCO/10%RC cases, there is a €309/year/member extra cost saving and 30kg/year/member extra CO_2 emission reduction in the latter case. Among the 4 cases discussed, with some policy support from government, the 30%LU/60%LUCO/10%RC spilt in the middle rollout areas in Dublin seem the most probable

projection for introducing CSS. This would save €453million/year for customers and if rolled out to the entire country, it would save €795million/year.

5.4 Discussion

This chapter developed and implemented a methodology which evaluated the feasibility and potential benefits of car sharing. This methodology was then applied to the population of Ireland, and the economic and environmental impacts of establishing a CSS were calculated. The inferences drawn from the analyses in the previous section and their implications for policy changes are discussed in this section.

The methodology developed is closely based on the findings previous research on car sharing, particularly the work of Loose (2010) and Martin and Shaheen (2010). It was designed to be universally applicable to regions where a CSS is being considered as an element of policy goals. Subject to the availability of adequate population travel and socio-demographic data, the methodology can be readily implemented elsewhere.

The geographic analysis indicated that there exists a large group of individuals (denoted as LU in the paper) who are quite likely to join CSS. It also identified the geographic concentration of these individuals in urban areas. A CSS is therefore potentially viable in these areas of Ireland.

The cost analysis indicated that owning a car significantly increases the annual travel related costs of an individual. Individuals who are not dependant on a privately owned car to satisfy the majority of their travel needs would save significantly on joining CSS. The non-car owners can join CSS as an alternative to purchasing a car as CSS would provide access to a car without bearing the ownership and maintenance costs. The car owners would also benefit by saving ownership and maintenance costs; however CSS membership may not replace their total need for car travel if they do not intend to change a percentage of their trips to more sustainable modes. The financial benefits gained by the LUCO and non-car owners on joining CSS makes a definite business case for introducing public or private CSS to Ireland.

The introduction of CSS would also provide significant CO_2 savings at all rollout stages. The more car owners join CSS, the bigger the environmental benefit will be. If policy changes are made to support wide-spread introduction of CSS, it can contribute to the National Climate Change Strategy (Deptartment of the Environment, Heritage, & Local, Government Ireland, 2007), prove to be a major step towards sustainability by promoting sustainable travel modes such as walking, cycling and public transport, by indirectly restricting car ownership levels and number of car trips.

It would also reduce congestion levels, parking space demand and other externalities associated with increased car mode share. The environmental benefits of CSS can be best realised through provision of electric cars as CS vehicles. This will promote the use of electric cars, further reduce CO_2 levels and may bring in private investment from electric car manufacturers.

Accordingly, even without much policy support CSS is viable as a business idea in areas with high population density within Dublin County. Outside Dublin, there is a lack of high density areas with suitable users. With governmental policy support such as tax incentive or work place mobility management schemes, a CSS could operate successfully in the major cities (Cork, Limerick, Galway) and other medium density areas in Ireland.

In the analysis of the ideal potential impact (Impact 2) of CSS the 30%LU/60%LUCO/10%RC spilt in the middle rollout areas in Dublin seems to be the most probable projection for introducing CSS. This would save approximately €453million/year for customers and 66.4kt CO2 emissions per annum in Dublin with electric cars. The figures will change based on the quality of infrastructure and operationalities of the CSS.

6 PARAMETERS AFFECTING SUCCESSFUL RIDE MATCHING

6.1 Introduction

This chapter evaluates how an online ride sharing service (RSS) might operate and what parameters influence an individual's chances of successfully identifying a match. Chapter 7 then builds on the ride matching work in this chapter to evaluate the economic and environmental impact of a ride sharing service operating in the Dublin area.

In section 1.1, ride sharing was defined as: two individuals, who are at best tenuously acquainted, using modern technology to arrange to share a common journey in a car which belongs to one of the individuals. Little is known about the willingness to ride share, and what is known is confused by a failure to distinguish between inter-household and intra-household sharing in much of the research. It is also confused by the developments of new technologies, specifically smart phone apps, which allow for the easy exchange of money, communication in the event of problems such as delay and the establishment of trust and reputation between strangers. This chapter therefore explores how changes in the behaviour of RSS registrants and the constraints applied to matches could impact on the match rates achieved in a real commuter population.

As discussed in section 2.3, previous research on ride sharing has reached contradictory conclusions. In their mathematical analysis, Tsao and Lin (1999) find that it is unlikely that individual commuters will be able to successfully identify other individuals with whom to share their commute journeys. In contrast, Agatz et al.'s (2011) model, which is based on simulated data from the Metro Atlanta region, finds that sustainable populations of dynamic ride sharers may be possible in relatively sprawling urban areas. Further to this, studies of commuters who ride share and initiatives which support ride sharing (e.g. Furuhata et al., 2013, Ghoseiri et al. 2011) have failed to identify the conditions under which commuters are most likely to successfully identify a match.

This chapter therefore seeks to answer the question: if using a Ride Sharing Service (RSS), under which realistic conditions and constraints are morning commuters most likely to successfully identify a match?

To answer this question a model is built in four stages. The model acts as an online RSS, on which commuters may register and offer or seek rides. It then identifies and assigns matches for these registrants. In analysing the model the POWSCAR dataset (CSO, 2012a) is used. This dataset provides real commuter data for the population of Ireland and is obtained from the 2011 Irish

Census. The dataset was described in section 3.2 and summary statistics were presented in section 3.3.

The first model, the base model, is a static model, i.e. all registrants have provided their details before the start of the matching process. In the base model, a RSS in the Dublin area proposes to match individual commuters on a particular day. The model begins with an initial pool of drivers offering to share their commute journey. K-means clustering, based on the home location, work location and arrival time of each driver is used to assign each driver to a cluster. Each driver offers a number of seats to potential passengers. An equal number of other users, i.e. passengers, then arrive seeking a suitable "match" for their morning commute journey. For each passenger, the cluster closest to that passenger is identified, and an exhaustive list of all possible matches within that cluster is compiled. This list is then reduced by applying constraints related to journey characteristics (origin to origin distance, destination to destination distance, and difference in desired arrival times). The resulting lists of acceptable matches for each passenger are combined into a master list of matches. Matches are then made in an iterative sequence. Passengers with only one possible match are identified and assigned a seat with a driver as appropriate. The matches are then prioritised according to the Euclidean distance between their journey and their driver's journey. Matches are then made in sequence. As drivers reach a quota of passengers their remaining matches are removed from the master list. At the end of the matching process the number of passenger matches and the number of driver matches is recorded.

In the second model, registrants have increased flexibility. In this model the ratio of driver registrants to passenger registrants is varied, i.e. the model examines cases where there are fewer drivers than passengers and vice versa. A new category of registrant is also introduced, these are termed flexible registrants. Flexible registrants are willing to act as either a driver or a passenger, provided a suitable match is found.

In the third model, the idea of social matching is introduced. While research in the area is limited, there are indications from existing RSSs that individuals are more likely to accept a match if the person they are matched with is similar to them. Therefore data on the age, gender and socio-economic group of each commuter is used to model how such preferences may affect match rates.

In the fourth and final model, the model moves from a static model to a dynamic model, i.e. not all registrants have registered with the RSS at the start of the matching process. The model again begins with a pool of registered drivers who are clustered based on the properties of their commute journey. A group (batch) of new registrants then arrives seeking a match. These new

registrants may seek a match as a) a driver, b) a passenger, or c) flexibly as either a driver or passenger, and they are therefore assigned as appropriate to the driver pool, the passenger pool or both. The matching process for the batch of new registrants then proceeds per the previous three models, until all possible matches are made. As appropriate additional checks are made to ensure that once a flexible registrant has been assigned a match with a specific role, any further matches with that registrant in the opposite role are removed from the master list of matches. When all possible matches are assigned, the algorithm then extracts a new batch of registrants. A simplifying assumption is made that all drivers with empty seats remaining continue to seek matches. A proportion of unmatched passengers from the previous batch may also be retained and continue to seek matches. This model is analysed by examining the effect of changes in the size of the initial pool of drivers, changes in the number of batches, and changes in the proportion of unmatched passengers retained on the overall match rate.

The rest of this chapter is laid out as follows. Section 6.2 provides a detailed description of the programming and statistical techniques used in identifying and assigning matches. Section 6.3 provides a detailed description of the individual steps used to process the data and subsequently calculate and assign matches in each model. Section 6.4 provides a summary description of the commuters and commute journeys on which the models are based. Sections 6.5 to 6.8 provide the results of the analyses carried out on each of the four models. The final section, section 6.9 provides a discussion of these results and draws conclusions based on the analyses described.

6.2 Programming and Statistical Techniques

The R programming language and a number of statistical techniques were employed both to build the models and to conduct the analyses described in this chapter. This section therefore briefly describes the statistical techniques used and the reasons for their selection.

6.2.1 The R Programming Language

The R Programming language was used to carry out the statistical analyses described below. R is a programming language developed for statistical computing and graphics. It was developed from the S programming language and is an open source software which is distributed freely under the GNU General Public Licence (R Development Core Team, 2013a).

R has the capability to implement a variety of statistical and graphical techniques. Its capabilities are also easily extended through the use of packages. Packages extend R by providing collections

of R functions, data, and compiled code in a defined format. Packages are made available through the CRAN family of Internet sites, and cover a wide range of modern statistical techniques and methodologies. Several packages were used to carry out the analyses described below, and these are described in the appropriate sections below (Ligges, 2003; R Development Core Team, 2008, 2013a).

6.2.2 K-means Clustering

When dealing with large datasets, such as the POWSCAR dataset (CSO, 2012a), grouping individual observations together through clustering is a popular method of reducing the processing burden. Observations with similar properties are clustered together. K-means clustering is a divisive, non-hierarchical method of defining clusters. The technique divides a set of observations into clusters, such that each observation belongs to the single cluster with the nearest mean. Clusters are defined based on Euclidean distances so as to reduce the variability of individuals within a cluster, while maximizing the variability between clusters (Kintigh & Ammerman, 1982), therefore the centroid (mean) of each cluster serves as a prototype for the cluster.

K-means clustering is particularly useful when dealing with large datasets, continuous variables, and data which does not have outliers. K-means clustering also offers flexibility as no observation is permanently committed to a cluster before the final iteration and appropriate clusters for new data points can be identified. Therefore it is the method utilised for this research.

In R, k-means clustering is carried out using the Hartigan and Wong (1979) algorithm. The algorithm partitions the observations into K groups such that the sum of squares of the observations to centre of their assigned cluster is a minimum. It is an iterative process, which uses the following steps to identify appropriate cluster centroids and assign data points to the appropriate clusters:

1. K centroids are chosen by selecting K data points at random whose properties function as K initial cluster centroids.
2. Each data point is assigned to its closest centroid.
3. The centroids are recalculated as the mean properties of all data points assigned to that cluster.
4. Each data point is then assigned to its closest centroid

5. Steps 3 and 4 are repeated until no data point is reassigned or the maximum number of iterations (specified to be 100 for this analysis) is reached.

In steps 2 and 4, the closest cluster is that with which a data point has the least Euclidean distance. That is each data point is assigned to the cluster with the smallest Euclidean distance between the data point and the cluster centroid.

Euclidean distance

Euclidean distance was used within the K-means clustering algorithm and subsequently to identify clusters for new members of the ride sharing service. In mathematics, the Euclidean distance or Euclidean metric is the "ordinary" distance between points, and is given by the Pythagorean formula. i.e. the square root of the sum of the squares of the differences between the corresponding coordinates of the points. In general, for an n-dimensional space, the distance is:

Equation 6.1: Formula to Calculate Euclidean Distance[3]

$$d(a,b) = \sqrt{(a_1 - b_1)^2 + \ldots + (a_i - b_i)^2 + \ldots + (a_n - b_n)^2} \qquad (6.1)$$

This formula is readily implemented in R using simple mathematical operations. Euclidean distance is used both to carry out k-means clustering and to identify and prioritise appropriate ride matches between commuters. The R code used to calculate Euclidean distance is presented in Appendix B.

Standardising Variables

While the variables used to calculate the centroids of the k-means clusters are continuous and have limited outliers, the calculation of Euclidean distance is affected by the relative values of the variables. In our case the some co-ordinates are in the range of 200,000 – 300,000 and have differences up to 50,000, while others range between 1 and 1440 with a maximum difference of 1440. These differences in scale could lead to additional importance (weight) being given to the larger co-ordinates when calculating Euclidean distance.

To remedy this, the scale function in R is used (R Development Core Team, 2013c), to rescale co-ordinates prior to the calculation of Euclidean distance and cluster centres. The scale function

[3] The symbols used in equation (6.1) are illustrative and are therefore not included in the list of symbols.

rescales the variables such that the mean of each variable is 0 and it has a standard deviation of 1. The ith value of a vector (V) with standard deviation σ_V is scaled as follows:

Equation 6.2: Equation to Scale Vectors prior to K-Means Clustering[4]

$$V_{i.Scaled} = \frac{(V_i - \overline{V})}{\sigma_V} \tag{6.2}$$

These scaled values of time and spatial co-ordinates were then used when carrying out the K-Means Clustering.

6.2.3 Random Sampling

The models make extensive use of random selection from the population of commuter drivers. This is carried out using the sample function in R (R Development Core Team, 2013a). The sample function is based on equations described by Ripley (2009, pp. 53-95), and it randomly selects a sample of a specified size from the elements of a list. The sample may be taken with replacement (elements of the list can be selected more than once), or without replacement (each element of the list can be selected at most once. An optional vector of probabilities may also be specified for elements of the list, making some elements more or less likely to be chosen than others. The R Code in which this function is used is provided in Appendix B.

6.2.4 GeoSpatial Analyses

Several R packages were used to perform geospatial functions such as drawing maps and the generation of random home locations..

Spatial sampling is also used to assign a random location co-ordinates within a Small Area identified in the POWSCAR database (CSO, 2012a) to individual commuters (n). This is carried out using the spsample function within the sp package in R. (Pebesma & Bivand, 2005; Bivand, Pebesma & Gomez-Rubio, 2013) The sp package is a package that provides a variety of utility functions and methods for spatial data, e.g. for plotting data as maps, spatial selection, as well as methods for retrieving coordinates, for subsetting, print, summary, etc. Within the sp package, the spsample function provides the facility to sample point locations within a specified area, using regular or random sampling methods; the method used is based on that described by Ripley

[4] The symbols used in equation (5.2) are illustrative and are therefore not included in the list of symbols.

(1981) and assumes that the geometry used is not spherical, so objects should be in planar coordinates. The rgdal package (Bivand, Keitt, & Rowlingson, 2013) was then used in conjunction with the gmodels package (Warnes, Bolker, Lumley & Johnson, 2012) to facilitate mapping of the model results.

6.3 Description of Model Algorithms

Following preparation of the dataset, the model is built in four steps with each additional stage incorporating additional features. The preparation of the dataset and the development of the model algorithms are now described.

6.3.1 The POWSCAR dataset

This section describes the preliminary steps taken to process the POWSCAR dataset into the dataset which was used in the analysis. The results of these preliminary steps are presented in section 6.4.

1. The initial population of interest is extracted from the POWSCAR dataset which provides annonymised details of the regular morning commute for all individuals who undertake a journey to work in the Republic of Ireland. The population of interest is adults who commute by driving, from a home location within county Dublin to a work location within county Dublin.
2. Home and work locations are then randomised within appropriate parameters to better mimic the characteristics of the real population. The dataset details a SA of residence for each individual (n). Using the SP package in R described in section 6.2.4, a random home location (X_{Hn}, Y_{Hn}) is generated within the appropriate SA for each individual (n). To carry out the spatial sampling, the Small Area boundary files, (Central Statistics Office, The Government of Ireland, & Ordnance Survey Ireland, 2011) were imported into R. For each individual commuter (n), the algorithm chose a random point within the specified Small Area, given in the POWSCAR dataset as their home location. The dataset provides a work location (destination) as an X, Y co-ordinate which is rounded to the nearest 250m grid square. A random work location (X_{Wn}, Y_{Wn}) is generated within the appropriate grid square for each individual (n).
3. A departure time (DT_n), to the nearest minute was generated for each individual (n) as follows. The dataset provides a departure time for each individual within one of 6 half

hour bands from 06:31 to 09:30, and two additional bands (before 06:30, after 09:30) The rate of departure at the midpoint of the 6 half hour bands was estimated as the average departure rate for that band. A frequency polygon was used to estimate the departure rates at intermittent points. An exponential curve was then fitted to the two additional bands and the periods 06:30 – 06:45 and 09:15 – 09:30, by selecting a rate such that the rate of departure at 06:45 and 09:15 was appropriate and that the sum of all individuals departing before 06:30 and after 09:30 was 27,601 and 42,762 respectively.

4. The journey time in minutes provided for each individual (n) is then added to the generated departure time (DT_n), and an arrival time (AT_n) is calculated.
5. The "as the crow flies" distance travelled by each individual (n) is calculated:

Equation 6.3: Home – Work Distance for an Individual (n)

$$Dist_n = \sqrt{(X_{Hn} - X_{Wn})^2 + (Y_{Hn} - Y_{Wn})^2} \quad (6.3)$$

6.3.2 Model 1: Base Case Matching Algorithm

The following section describes the Base Case Matching Algorithm (BCMA). The BCMA is further illustrated in the flowchart presented in Figure 6.1. The algorithm models a hypothetical online RSS where a number of drivers ($D_j \varepsilon D$) register the details of a planned journey, from their home (X_{Hj}, Y_{Hj}) to their workplace (X_{Wj}, Y_{Wj}) with an arrival time AT_j, and a number of available seats (S_j) with the ride sharing service. An equal number of passengers ($P_i \varepsilon P$) also register the details of their intended journey from their home (X_{Hi}, Y_{Hi}) to their workplace (X_{Wi}, Y_{Wi}) with an arrival time AT_i.

The RSS uses k-means clustering to assign all drivers (D_j) to a cluster (K_j), with each cluster containing an average of K drivers. For each passenger (P_i), the nearest cluster (K_i) is identified. Within this cluster, the algorithm then identifies possible matches ($M_{ij} \varepsilon M$) between Passengers (P_i) and Drivers (D_j), subject to constraints related to the distance between their respective homes ($Dist_H$), the distance between their respective workplaces ($Dist_W$), the sum of the distance between their respective homes and respective workplaces ($Dist_T$), and the difference between their desired arrival times (t). A list of all possible registrant matches is thus compiled. From the list of all matches (M), matches are assigned in an iterative process by prioritising first those passengers (P_i) with only one match ($\sum M_i = 1$) and subsequently the most closely matched passenger & driver combination.

To simplify the BCMA analysis, a set of base parameters were selected and the each parameter of interest was then varied in turn. Three representative levels of registration (D+P = 2%, 5% and 10% of the commuting population were used. The remaining base parameters were: a cluster size (K) of 10, a seat capacity (S) of 3, an allowable distance between the drivers and passengers respective homes ($Dist_H$) of 2km, an allowable distance between the drivers and passengers respective workplaces ($Dist_W$) of 2km, a total allowable distance ($Dist_T$) of 3km and an allowable gap between the drivers and passengers intended arrival times (t) of 20 minutes., were selected. The parameters (S, $Dist_H$, $Dist_W$, $Dist_T$ and t) were each varied in turn, and the impacts on the proportion of registrants finding a match were then examined.

The full matching algorithm is described in detail below and the results of the analyses are presented in section 6.5.

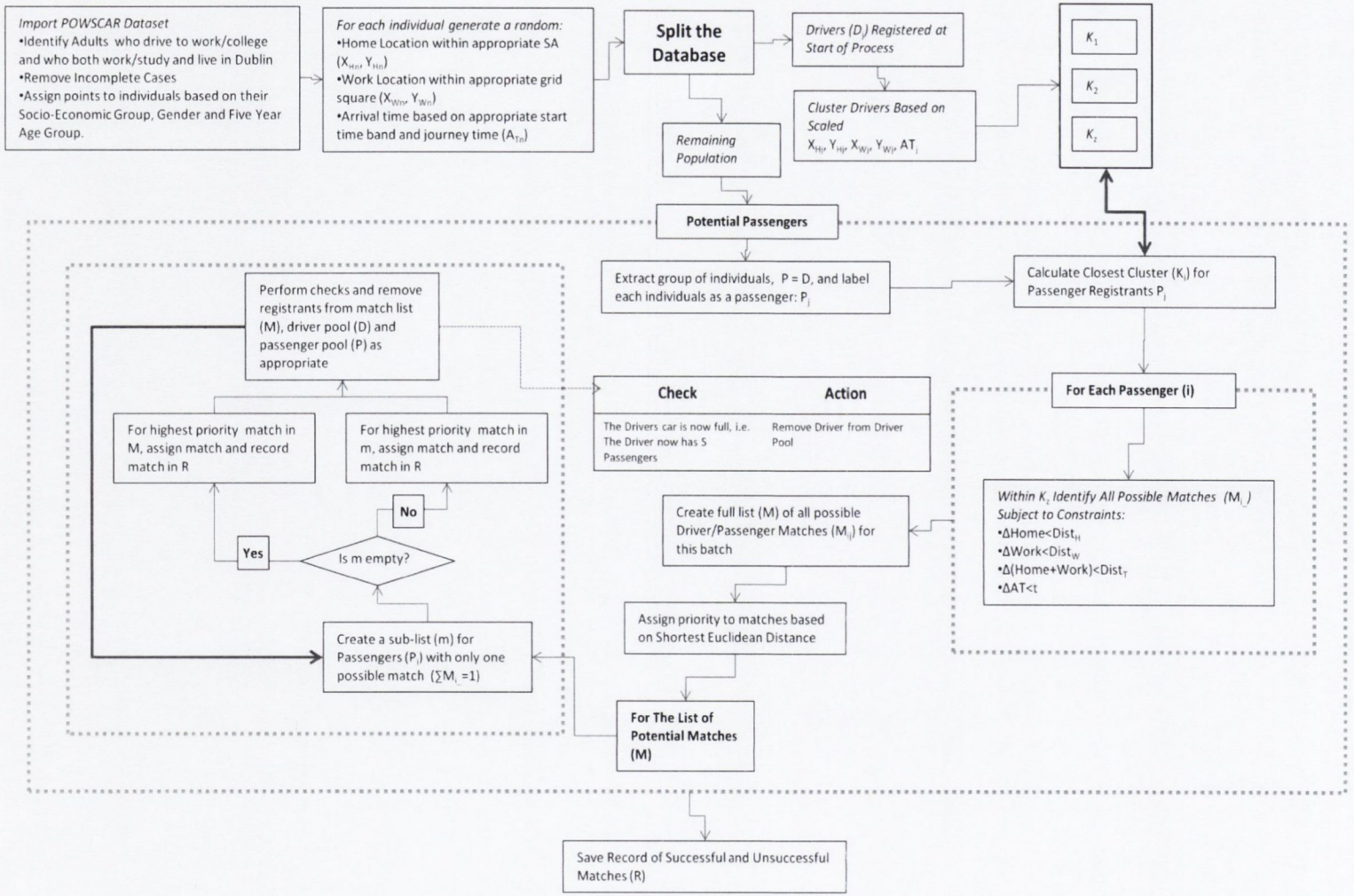

Figure 6.1: Flowchart of the Base Case Matching Algorithm

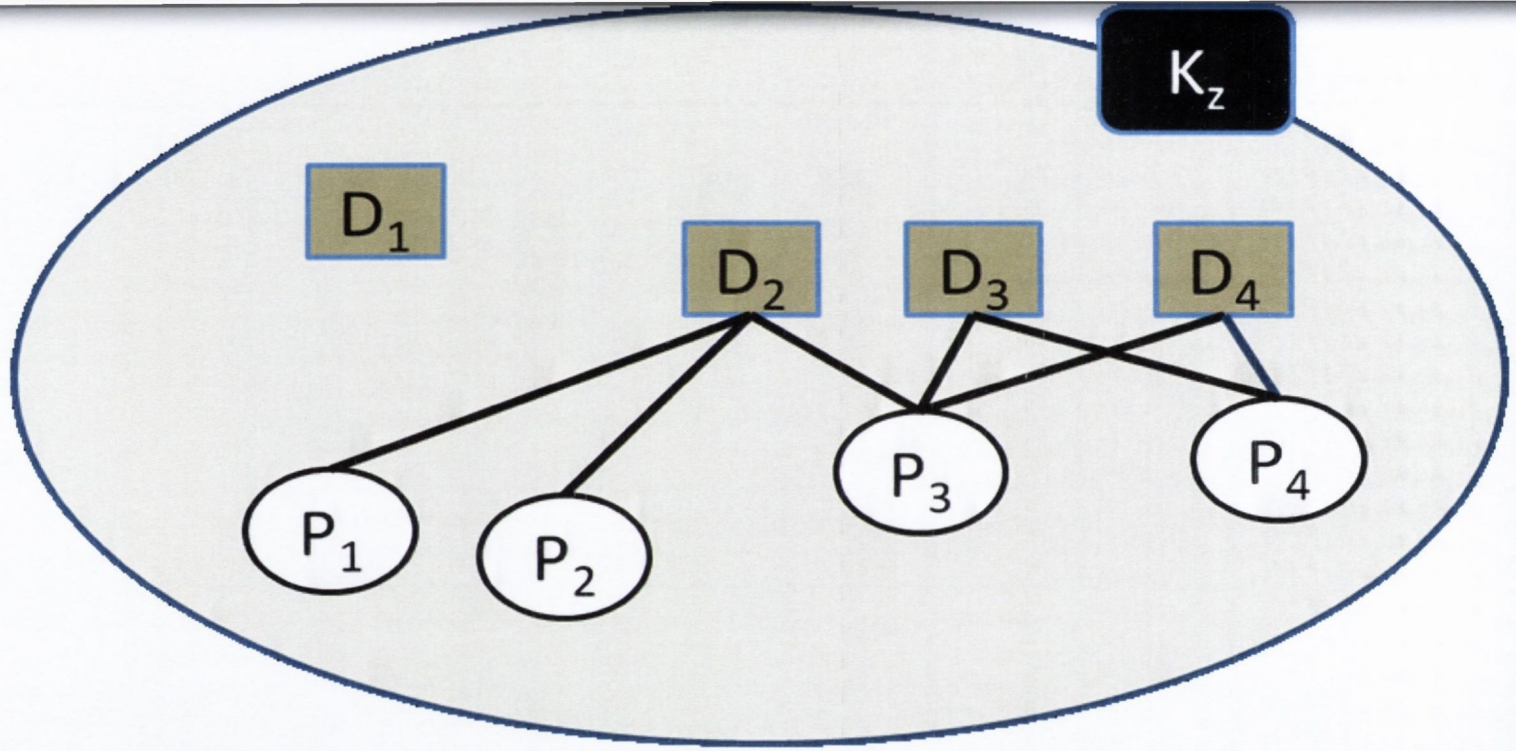

Figure 6.2: Illustration of Driver (D_1 – D_4) and Passenger (P_1 – P_4) Matches for a single cluster (K_z)

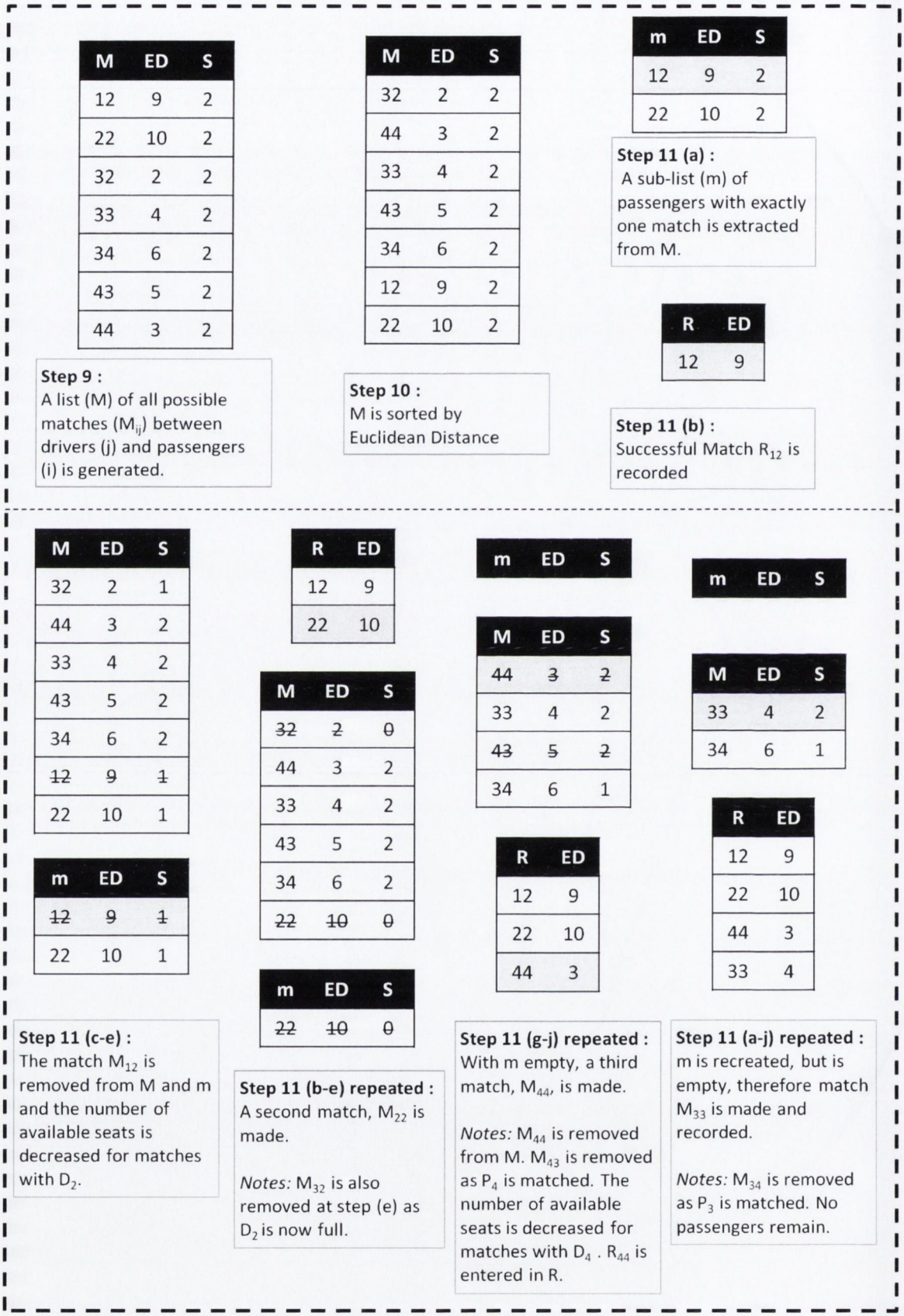

Figure 6.3: Illustration of the Matching Algorithm at Steps 9, 10 and 11.

BCMA Algorithm

The steps taken by the matching algorithm are provided below and further illustrated by Figures 6.2 and 6.3.

1. At random, select a group (D) of registering drivers (D_j) from the population. The process used for random selection is described in greater detail in section 6.2.3.
2. Scale the journey to work parameters of all drivers, such that each parameter (X_{Hj}, Y_{Hj}, X_{Wj}, Y_{Wj}, AT_j) has a mean of 0 and a standard deviation of 1. The scaling process provides (a) sample means, (b) sample standard deviations, and (c) scaled parameters which are calculated in accordance with Equation 6.4.

Equation 6.4: Calculation of Scaled Parameter Properties using (a) Mean, (b) Standard Deviation and (c) Scaled Parameters

$$\overline{X_H} = \frac{\sum_{j=1}^{D} X_{Hj}}{D}, \overline{Y_H} = \frac{\sum_{j=1}^{D} Y_{Hj}}{D}, \ldots \qquad 6.4\ (a)$$

$$\sigma_{X_H} = \sqrt{\frac{\sum_{j=1}^{D} \left(X_{Hj} - \overline{X_H}\right)^2}{D-1}}, \ldots \qquad 6.4\ (b)$$

$$\overline{\overline{X_{Hj}}} = \frac{\left(X_{Hj} - \overline{X_H}\right)}{\sigma_{X_H}}, \ldots \qquad 6.4\ (c)$$

A further explanation of the scaling process and the reasons for its use is provided in section 6.2.2.

3. Use k-means clustering to divide all registered drivers (D_j) into clusters (K_z) with K drivers in each cluster. The k-means clustering procedure is described in more detail in section 6.2.2. The centroid of each cluster (K_z) is calculated as an intrinsic part of the algorithm and is designated: $\left(\overline{\overline{X_{Hz}}}, \overline{\overline{Y_{Hz}}}, \overline{\overline{X_{Wz}}}, \overline{\overline{Y_{Wz}}}, \overline{\overline{AT_z}}\right)$
4. As at step 1, randomly select a group of registering Passengers (P), equal in number to D, from the remaining population of commuters.
5. Scale the journey parameters of each passenger (P_i), using the sample means and sample standard deviations calculated for the drivers (D) in Step 2, Equation 6.4; e.g. for P_i:

Equation 6.5: Scaling Passenger Parameters

$$\overline{\overline{X_{Hi}}} = \frac{\left(X_{Hi} - \overline{X_H}\right)}{\sigma_{X_H}}, \ldots \qquad (6.5)$$

6. For each passenger (P_i), identify the closest cluster (K_i) by calculating the Euclidean distance between the centroid of each cluster (K_z) and the passenger's scaled journey parameters.

Equation 6.6: Minimum Euclidean Distance Between Passenger and Cluster Centres

$$K_i = \min(ED_{iz}) = \min\left(\sqrt{\left(\overline{\overline{X_{Hi}}} - \overline{\overline{X_{Hz}}}\right)^2 + \left(\overline{\overline{Y_{Hi}}} - \overline{\overline{Y_{Hz}}}\right)^2 + \left(\overline{\overline{X_{Wi}}} - \overline{\overline{X_{Wz}}}\right)^2 + \left(\overline{\overline{Y_{Wi}}} - \overline{\overline{Y_{Wz}}}\right)^2 + \left(\overline{\overline{AT_i}} - \overline{\overline{AT_z}}\right)}\right) \quad (6.6)$$

A further explanation of Euclidean distance and the reasons for its use is provided in section 6.2.2.

7. For each passenger (P_i) generate a list of matches ($M_{ij} \varepsilon M_{i_}$), from the drivers ($D_j$) within K_i, who meet the relevant constraints i.e.

Equation 6.7: Distance Between Driver and Passenger (a) Homes, (b) Workplaces, (c) Home to Home & Work to Work and (d) Desired Arrival Times

$$Dist_H > \sqrt{\left(X_{Hi} - X_{Hj}\right)^2 + \left(Y_{Hi} - Y_{Hj}\right)^2} \quad 6.7\ (a)$$

$$Dist_W > \sqrt{\left(X_{Wi} - X_{Wj}\right)^2 + \left(Y_{Wi} - Y_{Wj}\right)^2} \quad 6.7\ (b)$$

$$Dist_T > \sqrt{\left(X_{Hi} - X_{Hj}\right)^2 + \left(Y_{Hi} - Y_{Hj}\right)^2} + \sqrt{\left(X_{Wi} - X_{Wj}\right)^2 + \left(Y_{Wi} - Y_{Wj}\right)^2} \quad 6.7\ (c)$$

$$t > \left|AT_i - AT_j\right| \quad 6.7\ (d)$$

8. For each valid match (M_{ij}), calculate the Euclidean distance (ED_{ij}) between P_i and D_j as:

Equation 6.8: Euclidean Distance Between Driver (j) and Passenger (i):

$$ED_{ij} = \sqrt{\left(\overline{\overline{X_{Hi}}} - \overline{\overline{X_{Hj}}}\right)^2 + \left(\overline{\overline{Y_{Hi}}} - \overline{\overline{Y_{Hj}}}\right)^2 + \left(\overline{\overline{X_{Wi}}} - \overline{\overline{X_{Wj}}}\right)^2 + \left(\overline{\overline{Y_{Wi}}} - \overline{\overline{Y_{Wj}}}\right)^2 + \left(\overline{\overline{AT_i}} - \overline{\overline{AT_j}}\right)} \quad (6.8)$$

9. For each registering passenger, repeat steps 5, 6, 7 and 8 thus generating a list of all possible matches (M) for all passengers. The results of this process and steps 10 and 11 are illustrated in Figures 6.1 and 6.2.
10. The list of matches (M) is ranked from smallest to largest value of ED_{ij}
11. Passenger – Driver matches are then assigned as follows:

a. A sub-list (m ε M) of passengers with exactly one match ($\sum M_{i_}=1$) is extracted, retaining the order of M
b. The passenger (P_i) in position m_1 is then assigned a seat with the matched driver (D_j) and a successful match is recorded R_{ij}
c. M_{ij} is removed from m and M.
d. The number seats available with driver D_j is decreased by 1:

$$S_j \leftarrow S_j - 1$$

e. The number of remaining seats with driver D_j is checked. If $S_j = 0$
    i. D_j is removed from D
    ii. Any matches $M_{_j}$ are removed from M and m
f. Steps b, c, d and e are repeated until no passengers with exactly one match remain
g. The passenger (P_i) in position M_1 is assigned a seat with the matched driver (D_j) and a successful match is recorded R_{ij}
h. M_{ij} is then removed from M and any further matches for P_i (i.e. $M_{i_}$) are removed from M
i. The number seats available with driver D_j is decreased by 1:

$$S_j \leftarrow S_j - 1$$

j. The number of remaining seats with driver D_j is checked. If $S_j = 0$
    i. D_j is removed from D
    ii. Any matches $M_{_j}$ are removed from M
k. Steps (a-j) are repeated until no possible passenger matches remain

12. The complete list of successful matches (R) is saved to an output file.

The result of the algorithm, for a single cluster, at the conclusion of step 7 is illustrated in Figure 6.2. In Figure 6.2, a group of drivers ($D_1 - D_4$) within a cluster K_z, have been matched with a group of passengers ($P_1 - P_4$). The presence of a match which meets the constraints is illustrated by a solid black line. Following the calculation of the Euclidean distance for each match at step 8, the progress of the algorithm through steps 9, 10 and 11 is illustrated and annotated in Figure 6.3. An assumption is made in this example, that each driver has the capacity for two passengers.

Figure 6.2 and Figure 6.3 also illustrate the value of prioritising passengers with only one match. Consider if at step 10, the matching algorithm proceeded directly by Euclidean distance. In order, the resulting matches would then be M_{32}, M_{44}, M_{12}, i.e. only three successful matches would take place as D_2 is now full, leaving P_2 unmatched.

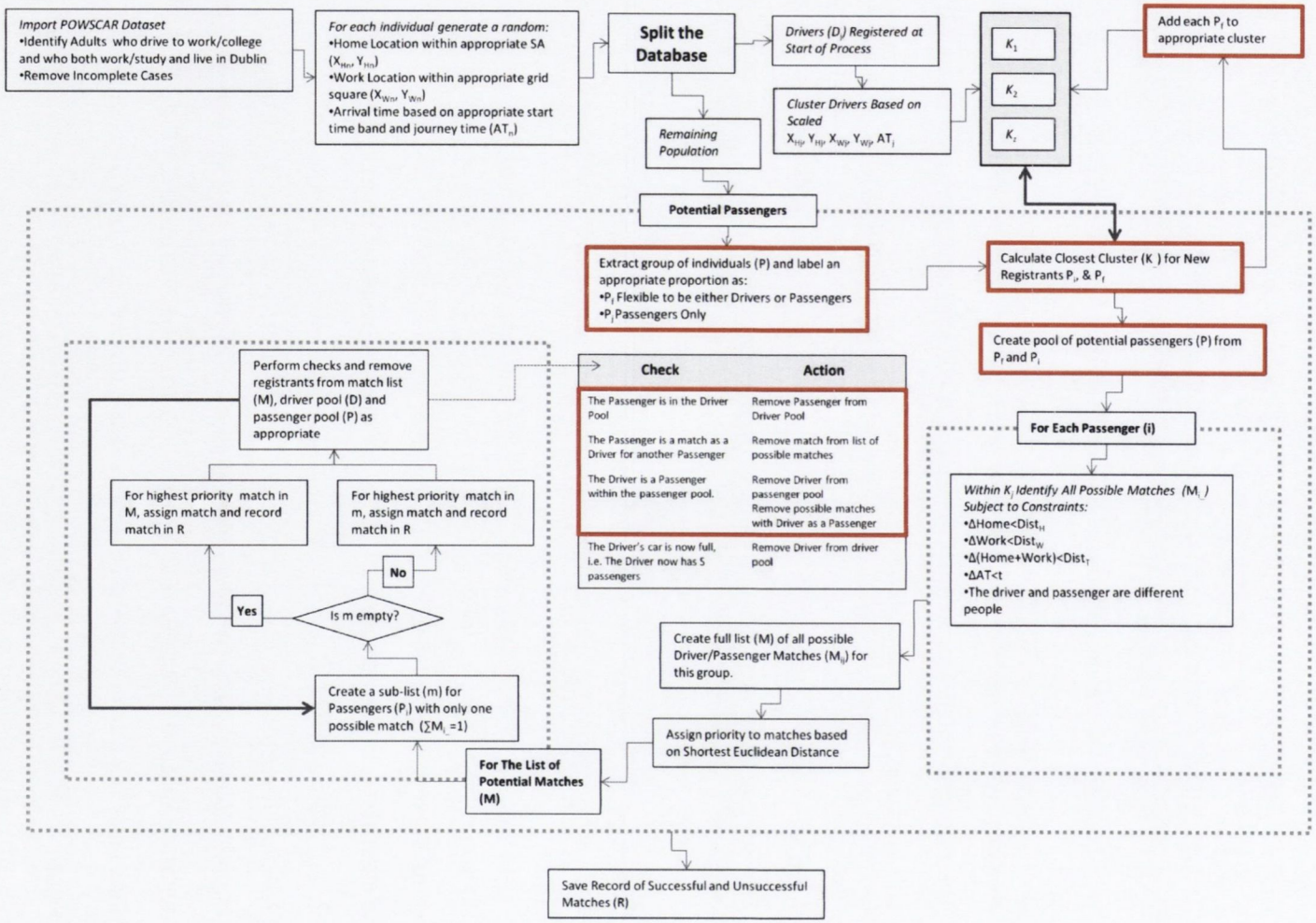

Figure 6.4: Flowchart of Flexible Matching Algorithm

6.3.3 Model 2: Flexible Matching Algorithm

The Flexible Matching Algorithm (FMA) is an iteration of the BCMA and is illustrated in Figure 6.5. In the BCMA, all registrants register as either a driver or a passenger, and the number of drivers and passengers is identical. The FMA represents a more realistic scenario, in which the respective numbers of passengers and drivers varies and some registrants (P_f) are flexible, i.e. they are willing to make the journey as either a driver or a passenger. Where "Passengers", or P are referred to in this and following section, it includes those who register seeking matches only as a Passenger (P_i) and those who register seeking matches as a driver or a passenger (P_f). In Figure 6.5, these changes to the BCMA (illustrated in Figure 6.1) are highlighted with red boxes.

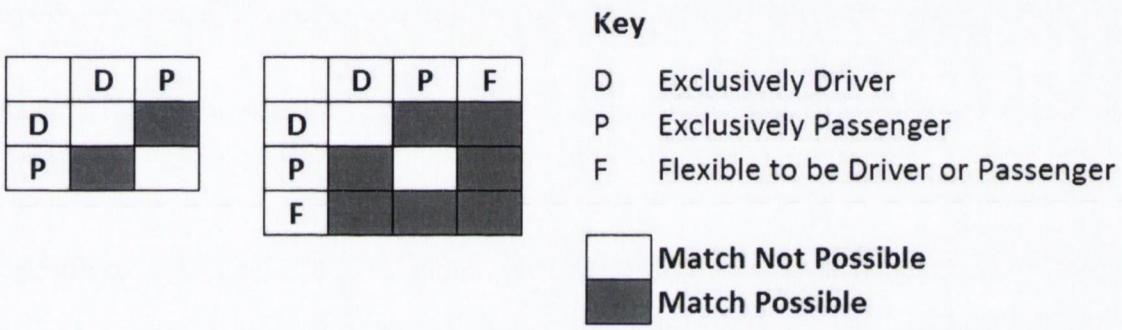

Figure 6.5: Improvement in Match Rates when the Flexible Role is Added

This model is expected to increase the number of matches achieved. Consider the simplest case where two registrants with similar journeys seek a match on a particular day. Under the BCMA each registrant has an equal chance of seeking a driver or passenger role. As illustrated in Figure 6.5, there are four possible resulting role combinations and of these two will create a match. Under the FMA, assume the same two registrants enter the system and each has an equal chance of being assigned a driver, passenger or a flexible role. As illustrated in Figure 6.5, there are nine equally possible resulting role combinations. Of these 9 combinations, 7 will create a match. For this simplified scenario, the introduction of the flexible role has increased the chance of an individual registrant from 50% to 78%.

In the analysis of the FMA, two parameters are varied. These are the number of drivers (D) with respect to the number of passengers (P) and the impact of varying proportion of passengers (P) who register as flexible registrants (P_f). The results of this analysis are presented in section 6.4.3.

Algorithm

The method of calculation is identical to that of the BCMA, with the following changes and substitutions:

1. Carry out Steps 1 – 3 as described in the BCMA
2. At BCMA Step 4, a registering group of passengers (P) is randomly selected from the population. P may be larger or smaller than D and includes individuals who are categorised as
    a. P_i – exclusively passengers,
    b. P_f – flexible to be either drivers or passengers.
3. At BCMA Step 5 the calculations performed for P_i are also carried out for passengers designated P_f
4. At BCMA Step 6, after the identification of appropriate passenger clusters, all flexible passengers (P_f) are added to the list of potential drivers (D) within their appropriate cluster. The *f* designation is then made redundant and all P_f are re-designated P_i. A single individual may therefore have both a driver designation (D_j) and a passenger designation (P_i).
5. At BCMA Step 7 an additional constraint (e) is added,
    e. that the Driver and the Passenger are not the same individual, i.e. $i \neq j$
6. Carry out Steps 8 – 10 as described in the BCMA
7. At BCMA Step 11, a number of additional checks are made at (c), (e), (h) and (j).
    a. At (c) and (h) two additional checks are made:
        i. Whether the passenger (P_i) is in the driver pool, ($P_i \varepsilon D$), in which case the passenger (P_i) is removed from pool of drivers (D).
        ii. Whether the passenger is a match as a driver for another passenger, ($\sum M_{_i} > 1$) in which case these matches are removed from the list of possible matches (M).
    b. At (e) and (j) two additional checks are made:
        i. Whether the driver is also a passenger ($D_j \varepsilon P$), in which case the driver (D_j) is removed from the pool of passengers (P).
        ii. Whether the driver (D_j) is a match as a passenger for another driver ($\sum M_{j_} > 1$) in which case these matches are removed from the list of possible matches (M).

8. The final step is identical to BCMA Step 12, i.e. the complete list of successful matches (R) is saved to an output file.

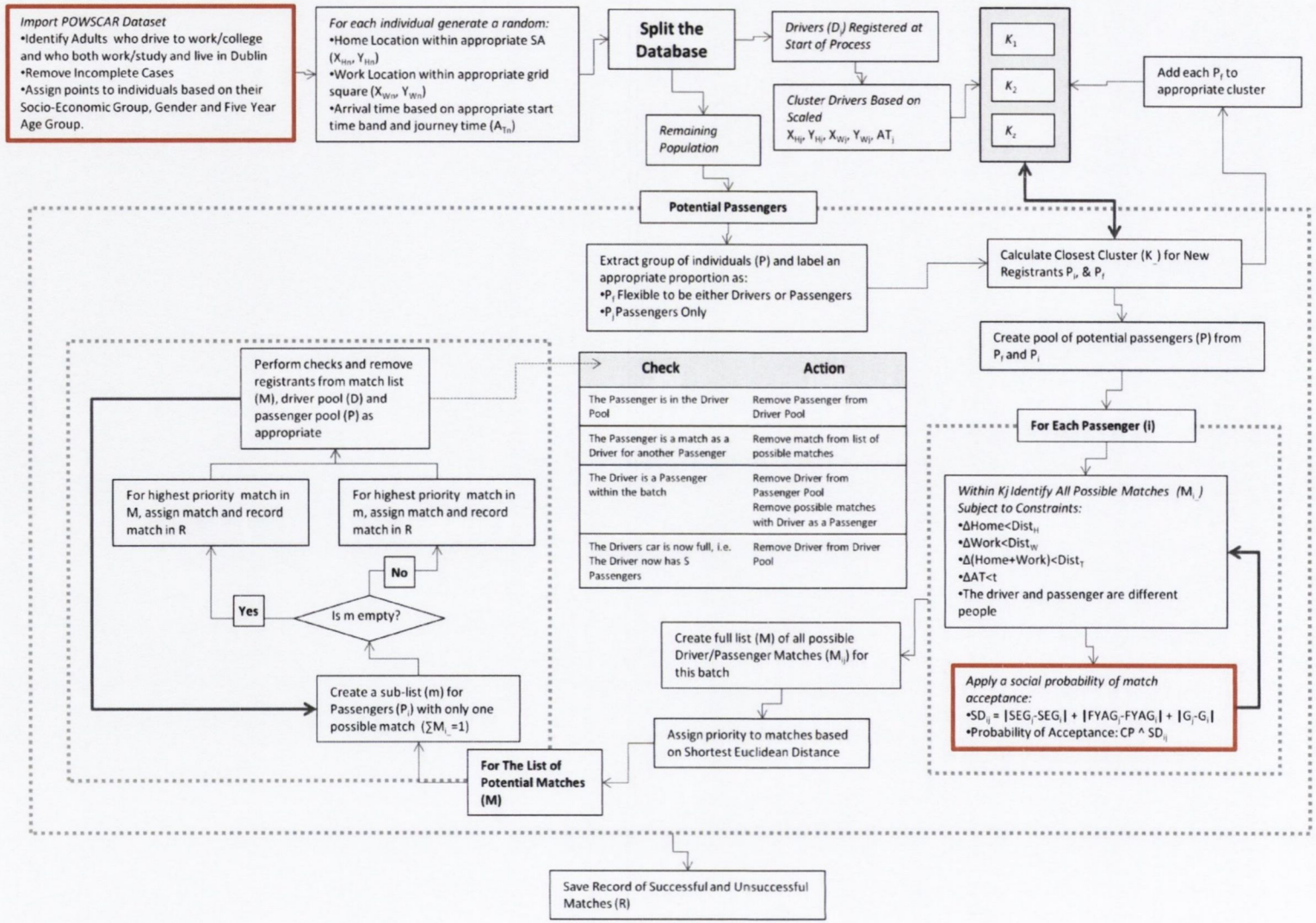

Figure 6.6: Flowchart of Social Matching Algorithm

6.3.4 Model 3: Social Matching Algorithm

The Social Matching Algorithm (SMA) is an iteration of FMA, which illustrates how a preference for matches with similar personal characteristics may influence the probability of an individual registrant attaining a match. It is illustrated in Figure 6.6, with differences to the FMA (illustrated in Figure 6.4) highlighted by boxes with red outlines.

Three personal characteristics – Age, Gender and Socio Economic Group, are used as a basis for evaluation. The POWSCAR database provides information about each of these three characteristics for each individual commuter. For each Match (M_{ij}) the algorithm calculates a social difference (SD_{ij}) based on the three parameters. A chance parameter (CP) is then used to calculate a probability of match acceptance. This probability is used with the sample function in R (described in section 6.2.3), to randomly either accept or reject the match.

Algorithm

The algorithm is then identical to that used for FMA, with the following additional changes to the BCMA algorithm:

1. Prior to the start of the matching process, each registrant is assigned a value for their socio-economic group, five year age group and gender.
    a. For each socio-economic group (SEG), the number allocated is:
        i. Employers and managers - 1
        ii. Higher professional - 2
        iii. Lower professional - 3
        iv. Non-manual - 4
        v. Manual skilled - 5
        vi. Semi-skilled -6
        vii. Unskilled -7
        viii. Own account workers - 3
        ix. Farmers - 3
        x. Agricultural workers - 6
        xi. All others gainfully occupied and unknown – 3
    b. For each five year age group(FYAG), the number allocated is:
        i. 15-19 - 1
        ii. 20-24 - 2
        iii. 25-29 - 3

iv. 30-34 - 4

v. 35-39 - 5

vi. 40-44 - 6

vii. 45-49 - 7

viii. 50-54 - 8

ix. 55-59 - 9

x. 60-64 - 10

xi. 65-69 - 11

xii. 70-74 - 12

xiii. 75+ - 13

c. For gender (G), the number allocated is:

i. Male – 2

ii. Female – 4

2. Carry out Steps 1 – 7 as described in the BCMA and modified by Steps 1-5 of the FMA
3. At BCMA, Step 7, an additional step, step (f) is added. This applies a social probability the match as follows.

a. The "social difference" between the matched driver and passenger is calculated as:

Equation 6.9: Social Difference Calculation

$$\mathrm{SD}_{ij} = \left|\mathrm{SEG}_i - SEG_j\right| + \left|\mathrm{FYAG}_i - \mathrm{FYAG}_j\right| + \left|G_i - G_j\right| \tag{6.9}$$

b. A probability of the match being accepted is then calculated as:

Equation 6.10: Probability of Match Being Accepted

$$probability = CP^{SD_{ij}} \tag{6.10}$$

c. As potential matches are calculated, this probability of acceptance is applied, and only acceptable matches are included for prioritisation at Step 5.

4. Carry out Steps 8 – 12 as described in the BCMA and modified by Steps 6-8 of the FMA

6.3.5 Model 4: Dynamic Matching Algorithm

The previous three models have represented static ride sharing, i.e. all driver and passenger requests are known before the start of the matching process. This model is illustrated in Figure 6.7 and is an iteration of the BCMA (illustrated in Figure 6.1) which includes a dynamic component and the flexible matching described in section 6.3.3, whereby there is an initial pool of drivers and

users subsequently register to seek matches as drivers, as passengers or flexibly (i.e. they are willing to act as either a driver or a passenger). To facilitate this, the matching algorithm is executed several times, once a sufficiently large "Batch" of additional users has registered. These differences between the Dynamic Matching Algorithm (DMA) and the SMA are highlighted by the red outlined boxes in Figure 6.7.

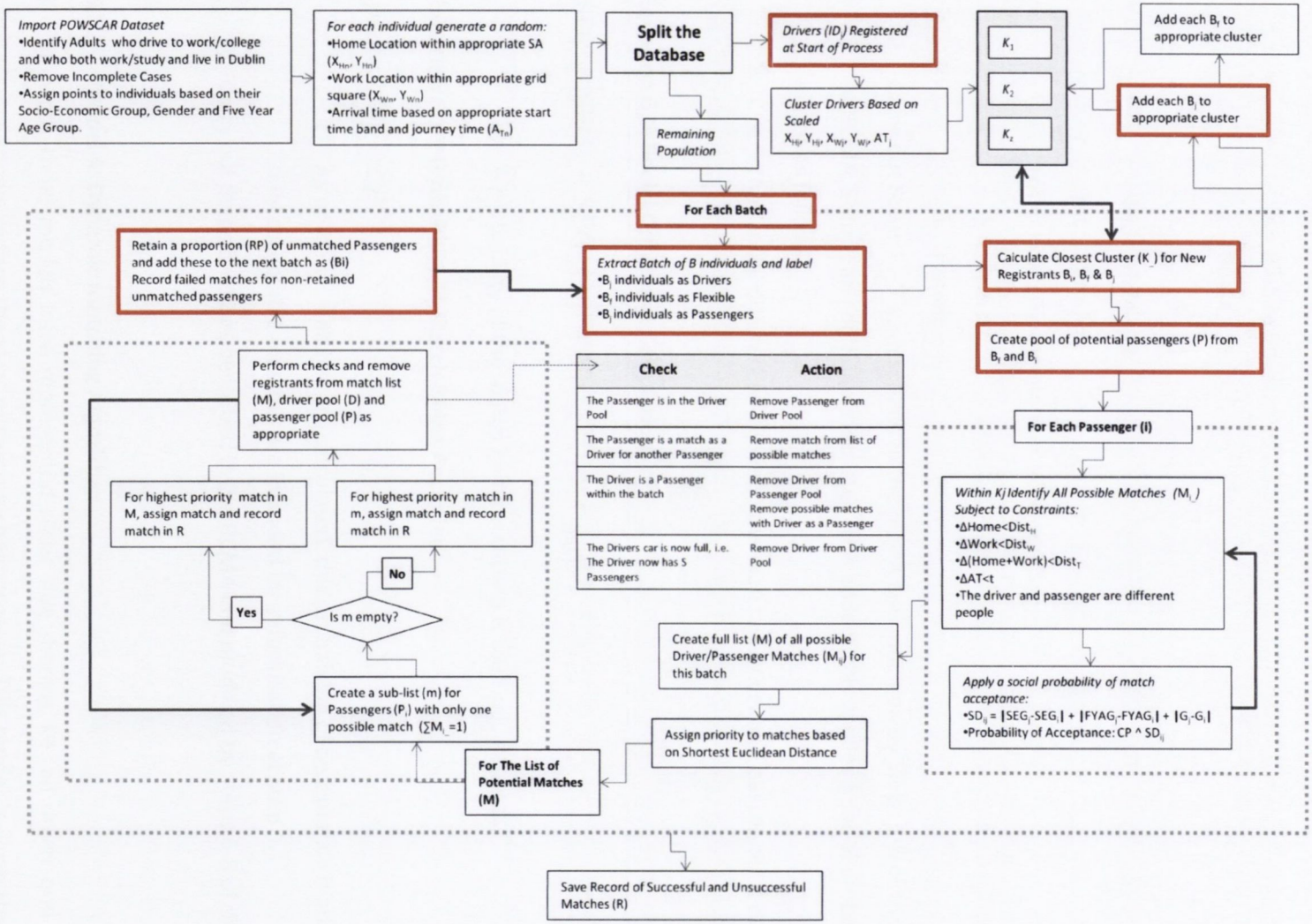

Figure 6.7: Flowchart of Dynamic Matching Algorithm

Drivers who register prior to the matching process are now designated ID_j, that is Initial Drivers, and cluster centroids are calculated using their journey details. More users then register. These newly registering users join as a batch, and may fall into one of three categories – Passengers Only (B_i), Drivers Only (B_j) or Flexible (B_f). For all new registrants, the appropriate cluster is identified. Newly registering drivers (B_j) are assigned to the driver pool. Newly registering passengers (B_i) are assigned to the passenger pool. Flexible registrants (B_f) are placed in both the passenger and driver pools. Flexible and passenger registrants are then matched as passengers in accordance with the algorithm described for models BCMA, FMA & SMA above, subject to the changes described below. When all matches have been calculated and assigned, a new batch of registrants is randomly selected from the remaining commuters. A proportion of the unmatched passengers (B_i & B_f) from previous batches may be included for matching with the new batch. This mimics a situation where different passengers have different time horizons within which to make a decision.

The DMA is analysed by examining the impact of (i) varying the number of Batches, (ii) varying the ratio between initial driver registrants (ID_j) and flexible registrants, passenger registrants and driver registrants (B_f:B_i:B_j) and (iii) the proportion of unmatched passengers included in the subsequent batch. The results of this analysis are presented in section 6.8. A simplifying assumption is made that any unmatched drivers (entering as B_j, B_f or ID_j) will make the journey with or without a match. They are therefore always retained as potential matches in the driver pool.

Algorithm

Figure 6.7 illustrates this algorithm in full. The algorithm for this matching is identical to the BCMA with the following changes:

1. Prior to the start of the matching process, each registrant is assigned a value for their socio-economic group, five year age group and gender as described in the SMA at step 1
2. At BCMA, Step 1, the group of drivers selected is a proportion of the total number of drivers desired in the final model, and is termed ID_j. Calculations performed at BCMA Step 2 and BCMA Step 3 are performed only for these drivers, and a list of potential drivers D, is then created.
3. At BCMA, Step 4, an initial batch of registrants (B) is randomly selected from the population. B may be larger or smaller than D and includes individuals who are categorised as

a. B_i – exclusively passengers,

b. B_f – flexible to be either drivers or passengers.

c. B_j – exclusively drivers

4. At BCMA Step 5 the calculations performed for P_i are carried out for passengers designated B_f , B_f , B_j

5. At BCMA Step 6, following the methodology described, appropriate clusters are identified for all new registrants, B_f , B_f , B_j. The following steps are then added:

   a. all flexible registrants (B_f) are added to the list of potential drivers (D) within their appropriate cluster.

   b. all driver registrants (B_j) are added to the list of potential drivers (D) within their appropriate cluster.

   c. all flexible registrants (B_f) and passenger registrants (B_i) are added to the list of potential passengers (P).

   d. The B_f, B_i, and B_j designations are then made redundant and are re-designated P_i and D_j as appropriate. A single individual may therefore have both a driver designation (D_j) and a passenger designation (P_i)

   e. Any unmatched passengers retained from previous batches are added to the list of passengers (P). Step 6 below provides further details.

6. At BCMA, Step 7, an additional constraint (e) and (f) are added,

   e. that the Driver and the Passenger are not the same individual, i.e. $i \neq j$

   f. The "social difference" and probability of match acceptance is calculated in line with the description given for the SMA Step 2.

7. At BCMA, Step 11, a number of additional checks are made at (c), (e), (h) and (j).

   a. At (c) and (h) two additional checks are made:

      i. Whether the passenger (P_i) is in the driver pool, ($P_i \varepsilon D$), in which case the passenger (P_i) is removed from pool of drivers (D).

      ii. Whether the passenger is a match as a driver for another passenger, ($\sum M_{_i} > 1$) in which case these matches are removed from the list of possible matches (M).

   b. At (e) and (j) two additional checks are made:

      i. Whether the driver is also a passenger ($D_j \varepsilon P$), in which case the driver (D_j) is removed from the pool of passengers (P).

ii. Whether the driver (D_j) is a match as a passenger for another driver ($\sum M_j > 1$) in which case these matches are removed from the list of possible matches (M).

8. At BCMA, Step 11, an additional step (l) is added. A proportion (RR) of the unmatched passengers, remaining at the end of a batch, are retained and added to subsequent batches at Step 5 (e) above. Those registering as B_j or B_f, are automatically retained within the driver pool, as it is assumed that those driving will make the journey whether or not they have passengers.
9. At BCMA, Steps 4 – 11 are repeated until the required numbers of registrants are processed.

Table 6.1: Descriptive Summary Data from Sample of Interest

County of Residence	Dublin City		South Dublin		Fingal		Dun Laoghaire Rathdown		County Dublin Total	
Gender	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
Total	29505	32143	23614	27970	26939	27773	18023	19061	98081	106947
Characteristics:										
Mean Household Size	3.1	2.9	3.3	3.1	3.3	3.1	3.3	3.1	3.3	3.1
Mean No. Vehicles/Household	1.7	1.7	1.9	1.9	1.9	1.9	2.0	1.9	1.9	1.8
Mean Journey Distance	6.0	5.2	7.5	6.4	10.8	9.3	7.7	6.1	8.0	6.7
Mean Journey Time	24.8	24.0	25.7	24.9	28.5	27.0	26.2	24.4	26.3	25.1
Mean Arrival Time	8:22	8:36	8:18	8:36	8:16	8:32	8:26	8:37	8:20	8:35
Number Working in:										
Dublin City	17137	21230	8997	10006	10877	11589	7250	6266	44261	49091
South Dublin	4101	3230	9802	13105	2555	1409	2509	1708	18967	19452
Fingal	5467	4834	1848	1254	12229	13930	858	434	20402	20452
Dun Laoghaire Rathdown	2800	2849	2967	3605	1278	845	7406	10653	14451	17952
Number in Age Bracket:										
15 - 29	5492	7309	4192	6010	4296	5363	2305	3056	16285	21738
30 - 44	12756	14358	10725	12587	13577	13864	7272	7876	44330	48685
45 - 60	9135	9029	7056	8099	7603	7486	6786	6834	30580	31448
60+	2122	1447	1641	1274	1463	1060	1660	1295	6886	5076
Number in Socio-Economic Groups:										
A - C	15797	17632	11585	12831	13863	13803	12866	11937	54111	56203
D - E	8711	11464	7825	12525	8488	11379	3507	6086	28531	41454
F - G	4007	2522	3403	2128	3558	2128	1112	685	12080	7463
Other	990	525	801	486	1030	463	538	353	3359	1827

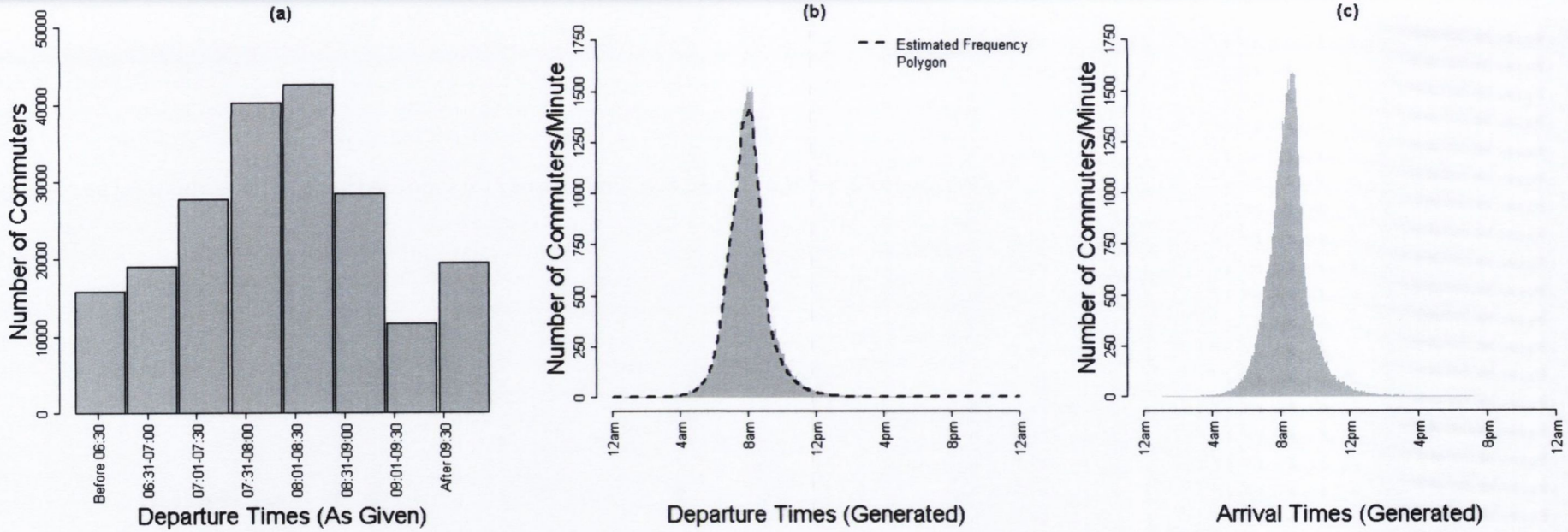

Figure 6.8: Population Departure and Arrival Times

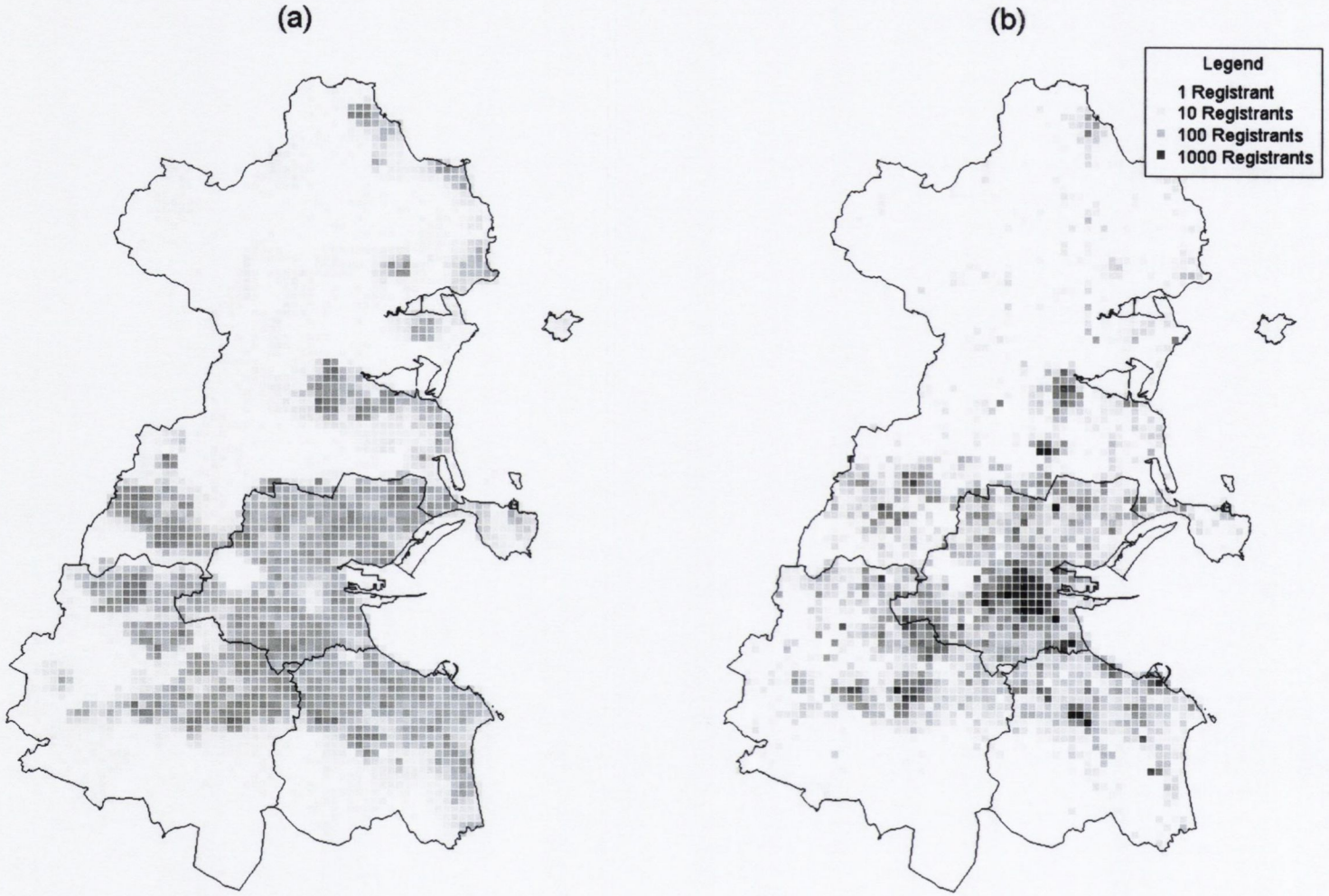

Figure 6.9: Generated (a) Home and (b) Work Locations for those commuting by Car to Work in county Dublin.

Figure 6.10: Indicative Journeys of Dublin's Driver Commuters, derived from POWSCAR dataset (CSO, 2012a)

6.4 Description of the POWSCAR dataset

During the preliminary phase of the analysis, the sample of interest (workers who commute from a home location within Dublin County to a work location within Dublin County by driving) was extracted from the POWSCAR dataset. This process identified 205,028 individuals who met these criteria. This section briefly describes the characteristics of the sample used as registrants during the analysis of the models.

Table 6.1 provides a summary of the characteristics of these individuals. Table 6.1 shows that the sample is almost evenly split between males and females, with males accounting for 47.8% of those meeting the selection criteria. There is little difference between the household and journey characteristics of the four administrative counties presented, however individuals residing in Fingal make longer journeys than those in the remaining areas. It is also worth noting that almost half of the sample (46%) works in the Dublin City area.

Figure 6.8 (a) illustrates the departure times of these individuals as provided in the POWSCAR dataset. The histogram shows a strong morning peak centred on 8am. As described in step 3, section 6.3.1 this information was used to generate a departure time in minutes and an arrival time in minutes for each individual. The resulting per minute departure rates are shown in Figure 6.8 (b) and the per minute arrival rates are shown in Figure 6.8 (c).

Figure 6.9 illustrates the density of (a) homes and (b) workplaces generated in step 2, section 6.3.1. In Figure 6.9 (a) the location of homes clearly shows an absence of car commuters in the city centre, which is surrounded by relatively high density inner suburbs and in the administrative areas of Fingal, South Dublin and Dun Laoghaire Rathdown peripheral towns with higher densities. The very low density of the Fingal area away from the sea is also clearly visible. In Figure 6.9 (b) the location of workplaces clearly shows the concentration of business within the city centre and in several large industrial estates along the M50 corridor and radial routes.

Figure 6.10 shows common origin – destination pairs for commuters in the dataset. To generate this map, home and work locations were rounded to the nearest kilometre and the frequency of each resulting home/work pair was calculated. All pairs with at least 25 commuters are shown in Figure 6.10.

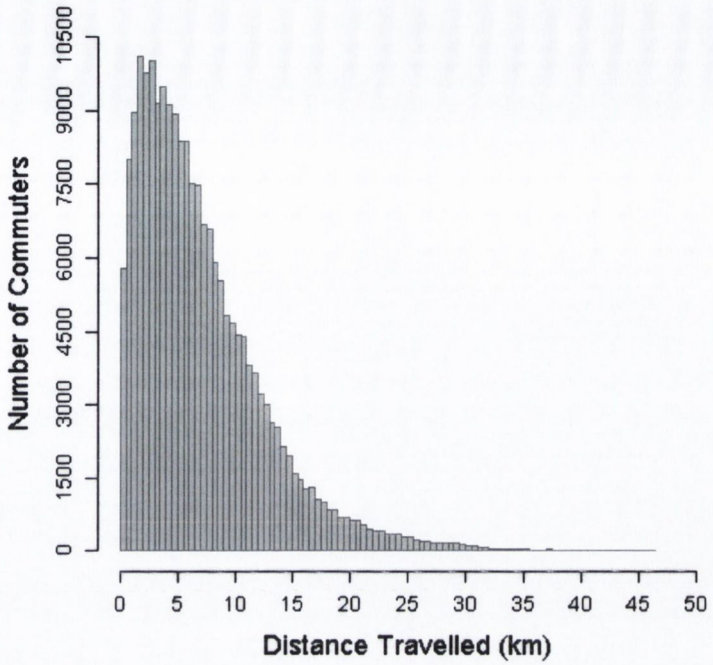

Figure 6.11: Distances Travelled (km), as the crow flies, by Commuters from Home to Work

Figure 6.11 presents a histogram of the Home-Work distance calculation carried out in step 5, section 6.3.1. Each bar represents a distance bracket of 0.5km. The mean, median and mode are 7.35km, 6km and 2km respectively.

6.5 Model 1 – Base Case Matching Algorithm

As described in section 6.3.2, the BCMA was analysed in two phases. The first phase examined the total number of registrants (D+P) and cluster size (K). In the second phase of the analysis, the other parameters of the model, the behaviour parameters (S, $Dist_H$, $Dist_W$, $Dist_T$ and t), are analysed.

The aim of this analysis is to evaluate the impact of each parameter on the ability of a RSS to successfully identify matches. The analysis is conducted by giving all parameters a preliminary setting and varying each parameter in turn. Of particular interest to this analysis is the relative impact of each behavioural parameter.

6.5.1 Parameters and Constraints Definition

Throughout this analysis, each parameter is set as follows unless otherwise stated in the discussion:

- Cluster Size (K) – 10
- Total Registrants (D+P) – 2050, 10252, 20502
- Total Drivers = Total Passengers (D=P)
- Seat Capacity (S) – 3
- Distance Between Homes ($Dist_H$) – 2km
- Distance Between Workplaces ($Dist_W$) – 2km
- Total Distance Between Homes and Between Workplaces ($Dist_T$) – 3km
- Difference in Desired Arrival Times (t) - 20

The analysis carried out and the results are now discussed in more detail.

6.5.2 Cluster Size

Cluster size is a parameter of the modelling method used. The algorithm searches for matches between a) passengers and b) drivers within the cluster closest to those passengers. The maximum number of matches for each passenger is therefore the number of drivers within a cluster. Since a longer list of potential matches takes longer for a computer to process, more drivers in a cluster increases the algorithms calculation time. However a short list of potential matches may exclude viable matches. This may be a particular problem when there are a large number of potential matches and drivers are more likely to become "full". The cluster size analysis was therefore carried out with the aim of balancing the competing demands of minimising calculation time and maximising the number of matches.

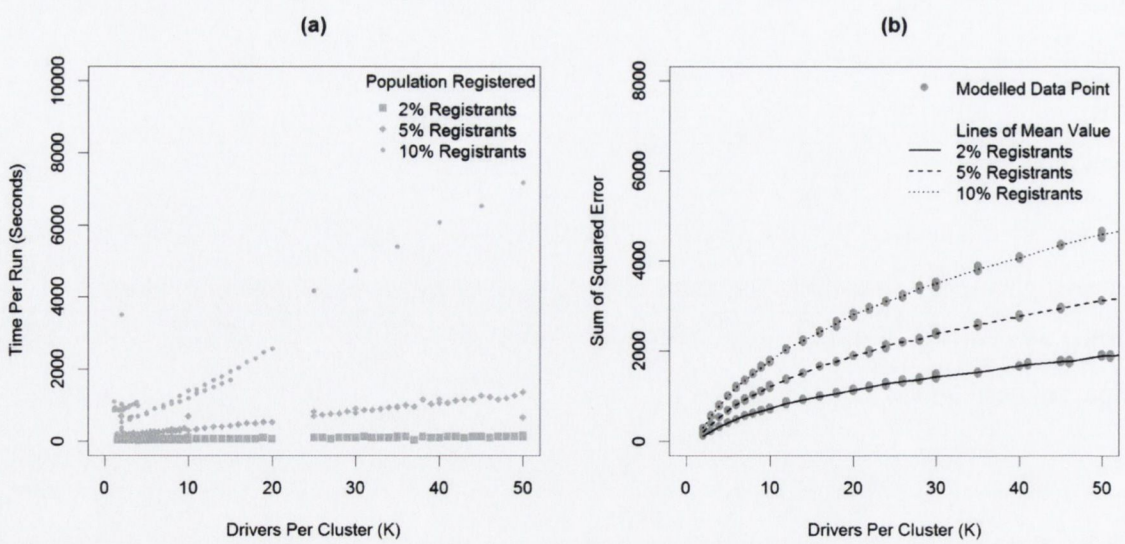

Figure 6.12: Impact of Cluster Size on (a) the time taken to run one instance of the model and (b) the Sum of the Squared Error within Each Cluster

Figure 6.12 (a) illustrates the impact of cluster size on the time taken to run a single instance of the model. The time taken is influenced by the specifications of the computer and by other processes which are running on the computer at the same time. However, in general, for the same computer and the same set of constraints, a larger cluster size results in a greater calculation time. The increase in calculation time is particularly acute where a large number of matches are expected, e.g. when 10% of the population register. As described in section 6.2.2, k-means clustering seeks to minimise the sum of the squares within each cluster. The optimal number of clusters is therefore frequently identified by examining how the sum of the squares (SSE) within each cluster varies as the number of clusters changes. Figure 6.12 (b) illustrates this relationship for the model. No single cluster size emerges as an optimum number, however in general fewer drivers in each cluster results in a (preferable) smaller sum of squares. Therefore from Figure 6.12 (a) and (b) it is concluded that the smallest cluster size which does not adversely impact on the number of matches made is considered desirable.

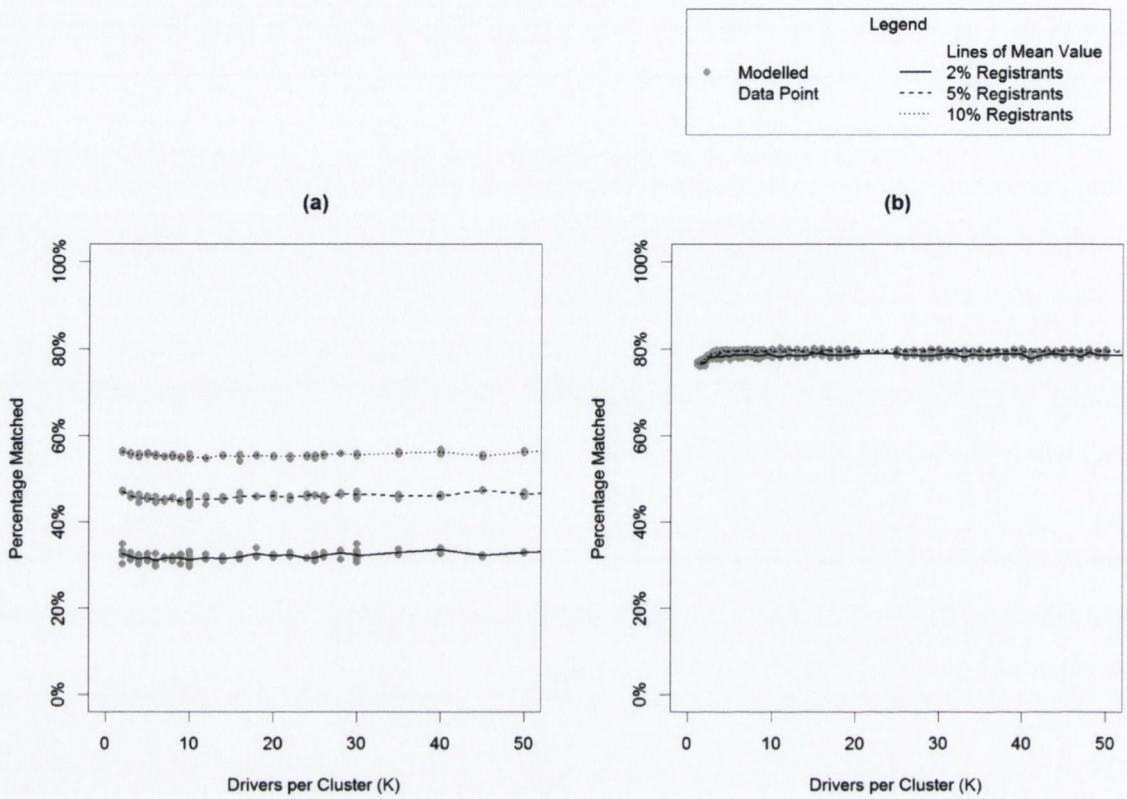

Figure 6.13: Cluster Size Vs Percentage of Registrants Achieving a Match with (a) Standard Constraints and (b) Relaxed Constraints

The relationship between the number of matches achieved and cluster size is therefore examined in Figure 6.13. Two separate cases are analysed, the base case described in section 6.5.1 above (Figure 6.13 (a)) and a case whereby the constraints $Dist_H$, $Dist_W$, $Dist_T$ and t are relaxed to increase the number of matches (Figure 6.13 (b)). In this relaxed condition, $Dist_H$, = $Dist_W$, = $Dist_T$ = 10km and t = 60 minutes. Figure 6.13 (a) and (b) illustrate that there is a region of instability between 0 and approximately 5 drivers per cluster where a link between the cluster size and the number of matches is apparent. Above 6 drivers per cluster, no influence of cluster size on the proportion of registrants achieving a match is identifiable.

As a result of these analyses a cluster size of ten was selected and used throughout the analysis of the models.

6.5.3 Total Number of Registrants (D+P)

This analysis examines the impact of varying the number of individuals registering with the RSS on the proportion of registrants who achieved a match.

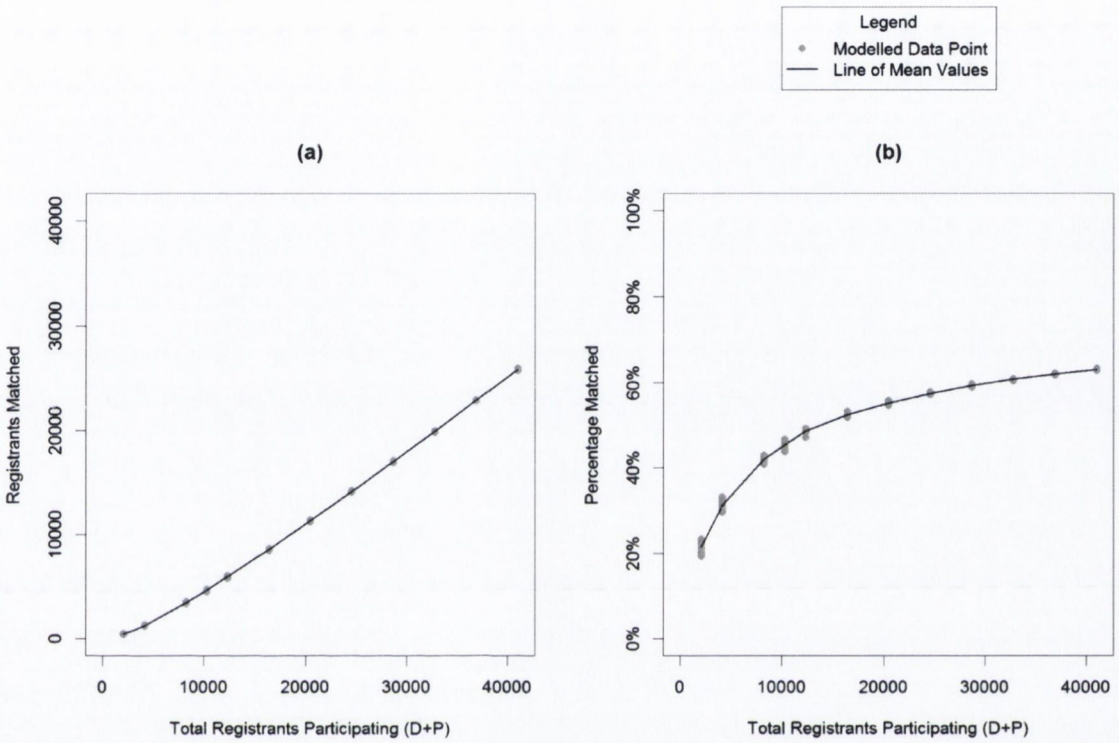

Figure 6.14: Total Registrants Participating Vs (a) Number of Registrants Achieving a Match and (b) Proportion of Registrants Achieving a Match

From the population of 205,028 commuters, a sample of between 1% (2050) and 20% (41006) registers with the RSS on a given day. Matching is then carried out using the BCMA and the number of registrants achieving a match is calculated. Figure 6.14 illustrates the results of the analysis. As expected, a greater number of registrants results in a higher proportion of those registrants achieving matches, however the relationship is not linear and greater gains are made by moving from 1% to 5% participation (24% increase in registrants achieving matches) than by moving from 5% to 20% participation (18% increase in those achieving matches).

Three values are therefore selected to illustrate the impact of changes to other parameters on the match rates achieved by each model. These are registrant numbers of 4101, 10252, 20502 which respectively correspond to 2%, 5% and 10% of the potential registrant population registering.

6.5.4 Behaviour Parameters

The behaviour parameters (S, $Dist_H$, $Dist_W$, $Dist_T$ and t) each relate to a registrants willingness to undergo inconvenience when participating in a ride-sharing service.

A registrant's willingness and ability to travel to a convenient point for pick up will increase the number of matches available to them. From a passengers perspective there may be a walk to the driver's home, workplace or a convenient pick up location. From a driver's perspective there may be a driven detour to the passenger's home, workplace or a convenient pick up location. The willingness of registrants to undergo such inconvenience will influence the probability of the ride-sharing service identifying a match. Similarly a registrant's flexibility of arrival time will increase the number of matches available to them, but may also incur inconvenience such as negotiation with work colleagues.

The final parameter considered here is the number of passengers each driver carries. Additional passengers may bring inconvenience by causing additional delay in the journey and through the discomfort attendant with sitting in the rear seat. On the other hand with appropriate pricing systems additional passengers may increase a driver's income and reduce other passenger's costs. The presence of a second or third passenger may also provide a sense of safety when sharing a car with a stranger.

Willingness to Travel to a Convenient Point ($Dist_H$, $Dist_W$, $Dist_T$)

A registrant's willingness to travel to convenient meeting locations clearly influences their chances of achieving a match. In this section the impact of a registrant's willingness to (i) detour from their home, (ii) from their work and (iii) the total detour they are willing to undertake while making a journey, on their chances of achieving a match are evaluated.

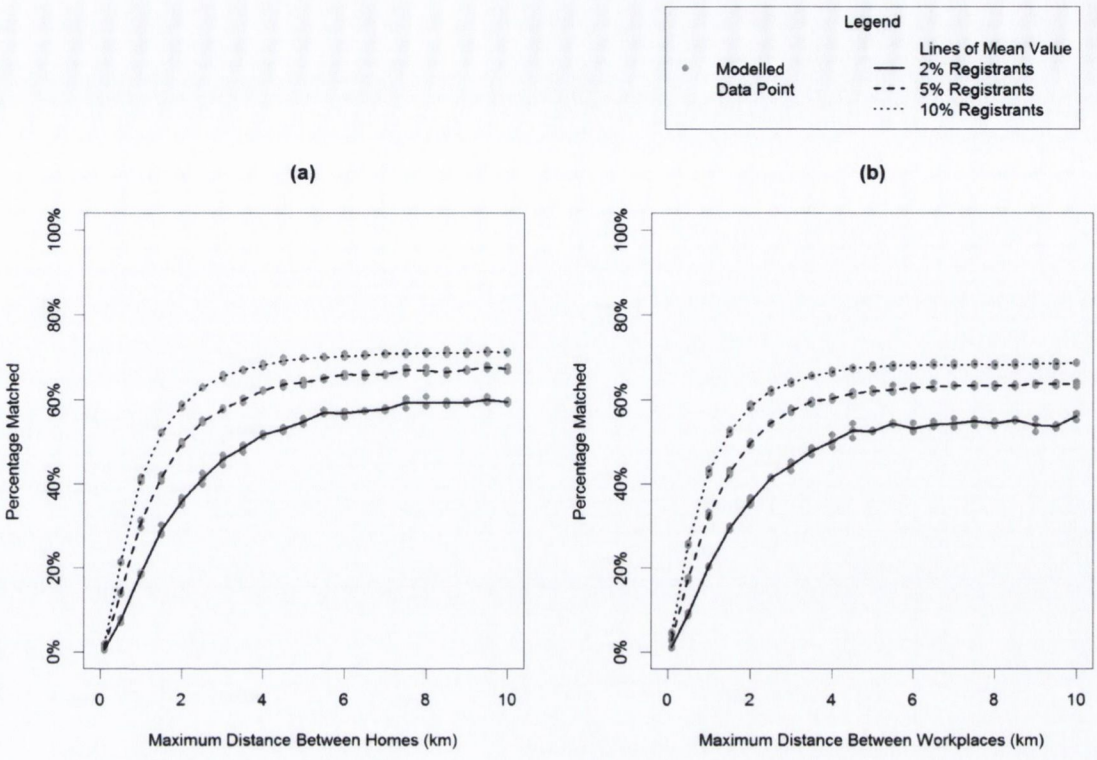

Figure 6.15: Acceptable Distance Between Driver and Passenger (a) Homes ($Dist_H$) and (b) Workplaces ($Dist_W$) Vs Percentage Matched

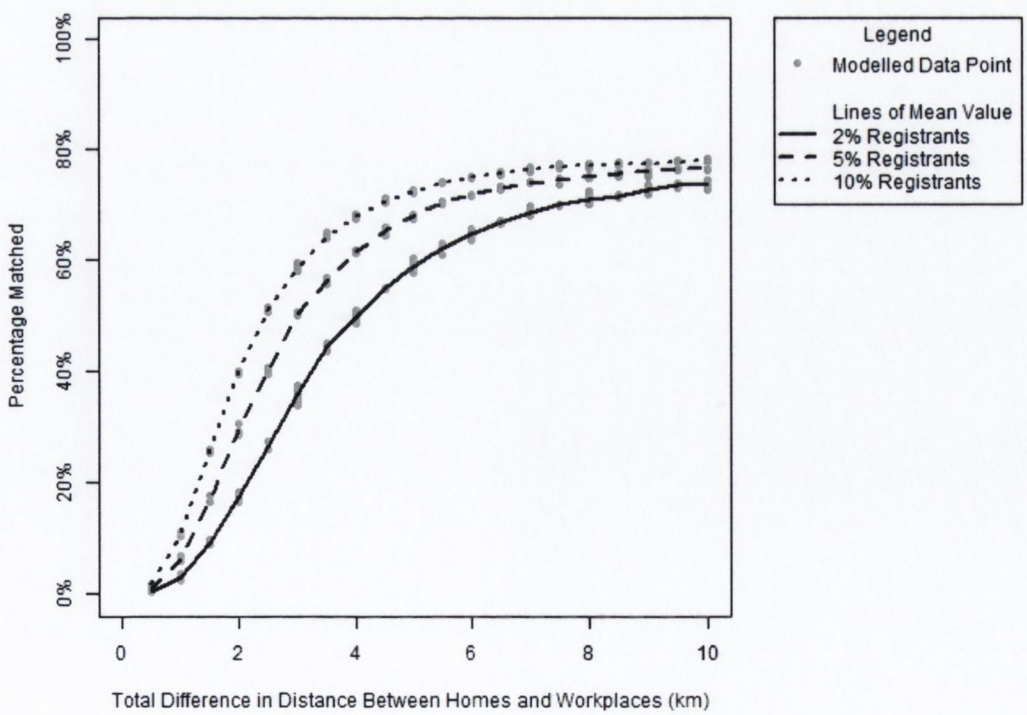

Figure 6.16: Acceptable Total Distance Between Driver and Passenger Homes and Driver and Passenger Workplaces ($Dist_T$) Vs Percentage Matched

It should be noted that when $Dist_H$ is being evaluated, $Dist_W$ remains at 2km per the base case throughout, while a limit for $Dist_T$ is set at $Dist_H + Dist_W$. Similarly for $Dist_W$, $Dist_H$ remains at 2km and $Dist_T$ is set at $Dist_H + Dist_W$. When $Dist_T$ is being evaluated, all three parameters are set to the value under evaluation, i.e. $Dist_T = Dist_H = Dist_W$. These changes are made to facilitate the independent evaluation of the three parameters.

For each of the three variables, tests were carried out on distances between 500m and 10km at 500m intervals. The results of the three analyses are presented in Figures 6.15 and 6.16.

As expected, a greater willingness to travel for a ride results in a greater chance of finding a match. For instance when 5% of the population register with the RSS, a $Dist_H$ of 1km achieves a match rate of 30.8%, increasing $Dist_H$ to 1.5km increases the match rate to 41.4%. $Dist_W$ exhibits a similar, though slightly steeper curve. At 1km $Dist_W$ has a 32.6% match rate and at 2km a 49.6% match rate. The benefits of increasing $Dist_H$ and $Dist_W$ diminish rapidly as the distances grow larger. Again at 5% registrants, an increase of $Dist_H$ from 4km to 10km provides only a 5.2% increase in the percentage of registrants matched.

From the three registrant populations shown (2%, 5% and 10%) we can also see that the benefits of increasing $Dist_H$ and $Dist_W$ vary with the number of individuals who register with the RSS. With 2% of the population registering, benefits from increasing $Dist_H$ and $Dist_W$ are appreciable up to approximately 4.5km whereas when 10% of the population registers, benefits from increasing $Dist_H$ and $Dist_W$ are appreciable only up to approximately 3km.

$Dist_T$, shown in Figure 6.16, shows a similar pattern to $Dist_H$ and $Dist_W$, i.e. a sharp increase in the percentage of registrants matched at first, followed by reduced gains at higher levels. With $Dist_T$ it should be noted, that because three seats are available with each driver, the maximum number of matches is artificially restricted. At the 10km limit, tor the 2%, 5% and 10% the proportion of passengers matched is 91%, 95% and 97% respectively.

Flexibility of Arrival Time (t)

In this section we examine the influence of an individual's willingness to vary their arrival time at work on the ability of the RSS to successfully identify a match. Figure 6.17 provides the results of testing the effect of different acceptable differences in desired arrival times on the proportion of registrants achieving a match.

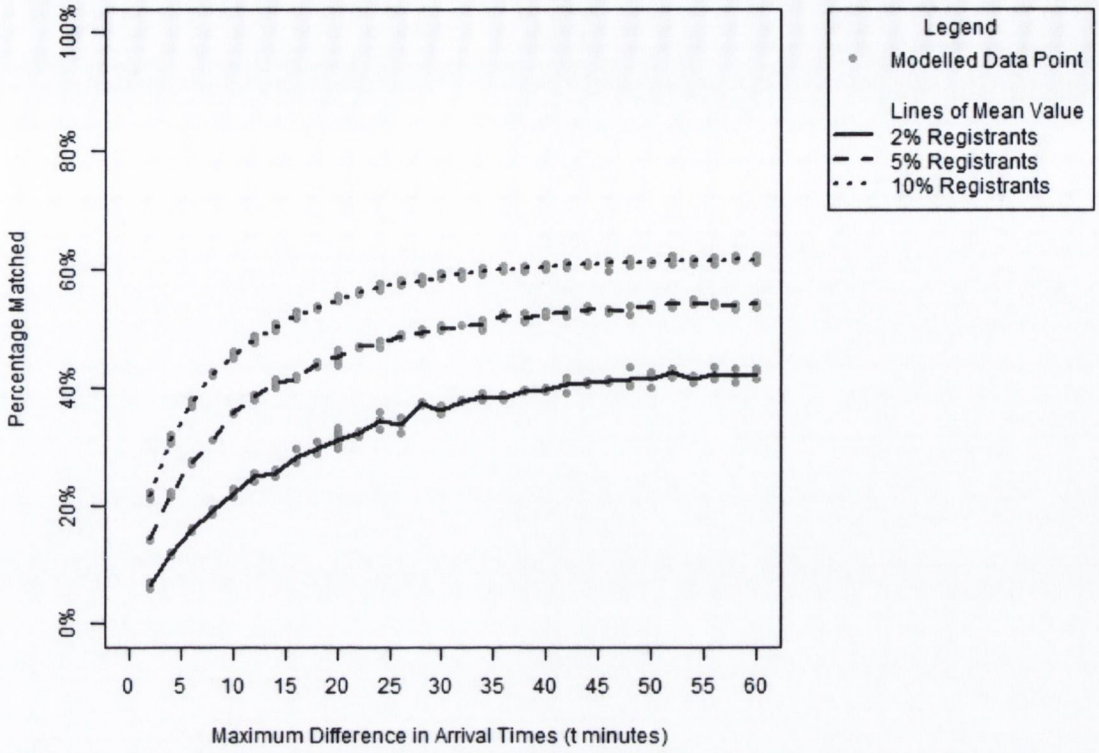

Figure 6.17: Proportion Matched Vs Acceptable Difference in Desired Arrival Times

Tests were carried out on differences between 1 and 60 minutes at two minute intervals. As expected, greater flexibility of arrival time increases the chances of a registrant finding a match and the curves are similar in shape to those presented in Figure 6.15 and Figure 6.16 for $Dist_H$, $Dist_W$ and $Dist_T$. However, even with a large number of registrants (10%) and good arrival time flexibility (60 minutes), the proportion of registrants achieving a match remains low at 61%. In contrast, $Dist_T$ achieved this match rate at 3.2km and further increases in match rate were available thereafter. While flexible arrival times can increase the chance of find a match it can be observed that a willingness to travel for a match has a greater overall potential impact.

Number of Passenger Seats (S) Available With Each Driver

This section presents the results of the analysis on how driver seat availability influences the overall match rate. The results of the analysis are presented in Table 6.2. In the context of the model allowing drivers to carry more passengers tends to increase the number of passengers achieving a match, and to decrease the number of drivers achieving a match. The proportion of drivers who are matched with more than one passenger also increases with the number of registrants. The impact of seat availability on the number of matches is therefore dependent on

the total number of registrants. This is because with fewer registrants, fewer drivers are likely to have more than one passenger, and in such cases the additional driver capacity remains unutilised. Overall the effects of an increased number of passenger matches and a decreased number of driver matches tend to cancel each other out.

Table 6.2: Effect of Varying the Number of Passenger Seats Per Driver on Match Rates

Number of Registrants	4101			10251			20503		
Available Seats	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Drivers									
Unmatched	1418.8	1483.4	1499.3	2821.4	3137.1	3214.9	4557.0	5499.5	5732.4
Matched	631.7	567.1	551.2	2304.1	1988.4	1910.6	5694.5	4752.0	4519.1
Drivers w/1 Passenger	*631.7*	*408.3*	*406.5*	*2304.1*	*1273.5*	*1272.3*	*5694.5*	*2804.8*	*2812.0*
Drivers w/2 Passengers	*0.0*	*158.8*	*109.7*	*0.0*	*715.0*	*441.8*	*0.0*	*1947.2*	*1137.2*
Drivers w/3 Passengers	*0.0*	*0.0*	*35.0*	*0.0*	*0.0*	*196.5*	*0.0*	*0.0*	*569.9*
Passengers									
Unmatched	1418.8	1324.6	1319.7	2821.4	2422.1	2380.1	4557.0	3552.3	3455.4
Matched	631.7	725.9	730.8	2304.1	2703.4	2745.4	5694.5	6699.2	6796.1
Match Rates									
Passengers	30.8%	35.4%	35.6%	45.0%	52.7%	53.6%	55.5%	65.3%	66.3%
Drivers	30.8%	27.7%	26.9%	45.0%	38.8%	37.3%	55.5%	46.4%	44.1%
Total	30.8%	31.5%	31.3%	45.0%	45.8%	45.4%	55.5%	55.9%	55.2%

Therefore increasing and decreasing driver capacity has little or no overall impact on the proportion of registrants who achieve a match.

6.6 Model 2: Flexible Matching Algorithm

The flexible matching algorithm tests the impact of varying the ratio of drivers to passengers on the number of matches made. This is tested in two ways – first by varying the number of drivers with respect to the number of passengers, and second by allowing passengers to register as either "flexible" or as "exclusively passengers". Those who register as flexible are willing to act as either a passenger or a driver in a match situation. As with the BCMA, this is a static model in that the journey details of all registrants are available prior to the start of the matching process.

To simplify the presentation of results, three cases are used to illustrate the analysis. These cases represent different proportions of the population registering and operating under differing constraints. As it was identified in section 6.5.4, that driver capacity (S) has little impact on the match rate, for each case the number of available seats (S) with each driver is 3, however this

issue is further examined in section 6.6.4. The remaining constraints for each case are described below, and the expected resulting match rates are summarised in Table 6.3.

- *Case 1:* This case is used to illustrate a pioneer membership, the number of registrants is low (2% of the population or 4101 in total), however these registrants are willing to make matches provided:
    - $Dist_H < 3km$
    - $Dist_W < 3km$
    - $Dist_T < 5km$
    - $t < 30$ minutes
- *Case 2:* This case is identical to the 5% case used under the BCMA, and thus facilitates easy comparison of results. The number of registrants is reasonable (5% of the population or 10,252 in total), and these registrants are willing to make matches provided:
    - $Dist_H < 2km$
    - $Dist_W < 2km$
    - $Dist_T < 3km$
    - $t < 20$ minutes

Table 6.3: Expected Results under Case 1, Case 2 and Case 3

	Case 1				Case 2				Case 3			
			95% Conf Int.				95% Conf Int.				95% Conf Int.	
	Mean	St. Dev	Upper	Lower	Mean	St. Dev	Upper	Lower	Mean	St. Dev	Upper	Lower
Drivers												
Unmatched	1106.7	16.5	1108.6	1104.8	3209.0	56.7	3216.6	3201.5	9184.7	27.1	9188.5	9180.9
Matched	943.3	43.7	948.3	938.2	1917.0	79.3	1927.5	1906.4	1067.3	39.3	1072.8	1061.8
Drivers w/1 Passenger	*573.5*	*20.7*	*575.9*	*571.1*	*1273.4*	*37.7*	*1278.4*	*1268.3*	*933.3*	*25.1*	*936.8*	*929.8*
Drivers w/2 Passengers	*239.1*	*13.6*	*240.7*	*237.5*	*445.1*	*24.4*	*448.4*	*441.9*	*116.1*	*10.0*	*117.5*	*114.7*
Drivers w/3 Passengers	*130.7*	*9.4*	*131.8*	*129.6*	*198.5*	*17.3*	*200.8*	*196.2*	*17.9*	*4.2*	*18.5*	*17.3*
Passengers												
Unmatched	607.3	21.5	609.7	604.8	2365.9	97.2	2378.8	2353.0	9031.8	34.4	9036.6	9026.9
Matched	1443.7	21.5	1446.2	1441.3	2759.1	97.2	2772.0	2746.2	1219.2	34.4	1224.1	1214.4
Match Rates												
Passengers	70.4%	50.0%	70.3%	70.4%	53.8%	50.0%	53.8%	53.9%	11.9%	50.0%	11.9%	11.9%
Drivers	46.0%	72.6%	46.1%	45.9%	37.4%	58.3%	37.5%	37.3%	10.4%	59.2%	10.5%	10.4%
Total	58.2%	63.2%	58.2%	58.2%	45.6%	53.4%	45.6%	45.6%	11.2%	54.5%	11.2%	11.1%

- *Case 3:* This case is used to illustrate a higher level of uptake within the population, but where registrants are less willing to undergo inconvenience when ride sharing. 10% (20,502 individuals) of the population register with the service; however ride sharing is only undertaken when both the driver and passenger journey match closely. Matches must meet the following constraints:
    - $Dist_H < 0.75km$
    - $Dist_W < 0.75km$
    - $Dist_T < 1.25km$
    - $t < 15$ minutes

6.6.1 Driver to Passenger Ratio

The analyses conducted under the BCMA considered only instances where the number of drivers was equal to the number of passengers, i.e. D/P=1. In this analysis the relationship between the number of matches achieved and D/P is examined. For simplicity, this set of analyses includes no flexible registrants ($\sum P_f=0$). Figure 6.18 presents the results of this analysis, breaking down the result by (a) the proportion of registrants, (b) the proportion of passengers, and (c) the proportion of drivers who achieve a match. In Figure 6.18 (c) drivers achieve a match when they carry at least one passenger.

Figure 6.18 (a) illustrates that by reducing the number of drivers with respect to the number of passengers (D/P < 1), the total number of matches achieved can be significantly increased. Figure 6.18 (b) and Figure 6.18 (c) illustrate more clearly what is happening. When D/P falls below 1, the number of drivers achieving a match increases more quickly than the number of passengers achieving a match falls.

When the number of drivers is increased with respect to the number of passengers (D/P > 1), the overall match rate falls. Figure 6.18 (b) illustrates that increasing the number of drivers does not increase the number of passengers who achieve a match, i.e. for values of D/P above 1.5 the curves for each of the three cases are relatively flat. Even when D/P first goes below 1, there is only a small change in the proportion of passengers achieving a match. In all three graphs (a – c), the flatter curve of Case 3 illustrates that with narrow constraints, the benefits of reducing D/P are not gained. However, the three cases follow roughly the same paths, suggesting that beyond this there is little interaction between the D/P ratio and the behavioural constraints.

In summary having fewer registrants seeking a driver role and more registrants seeking a passenger role results in a higher total match rate.

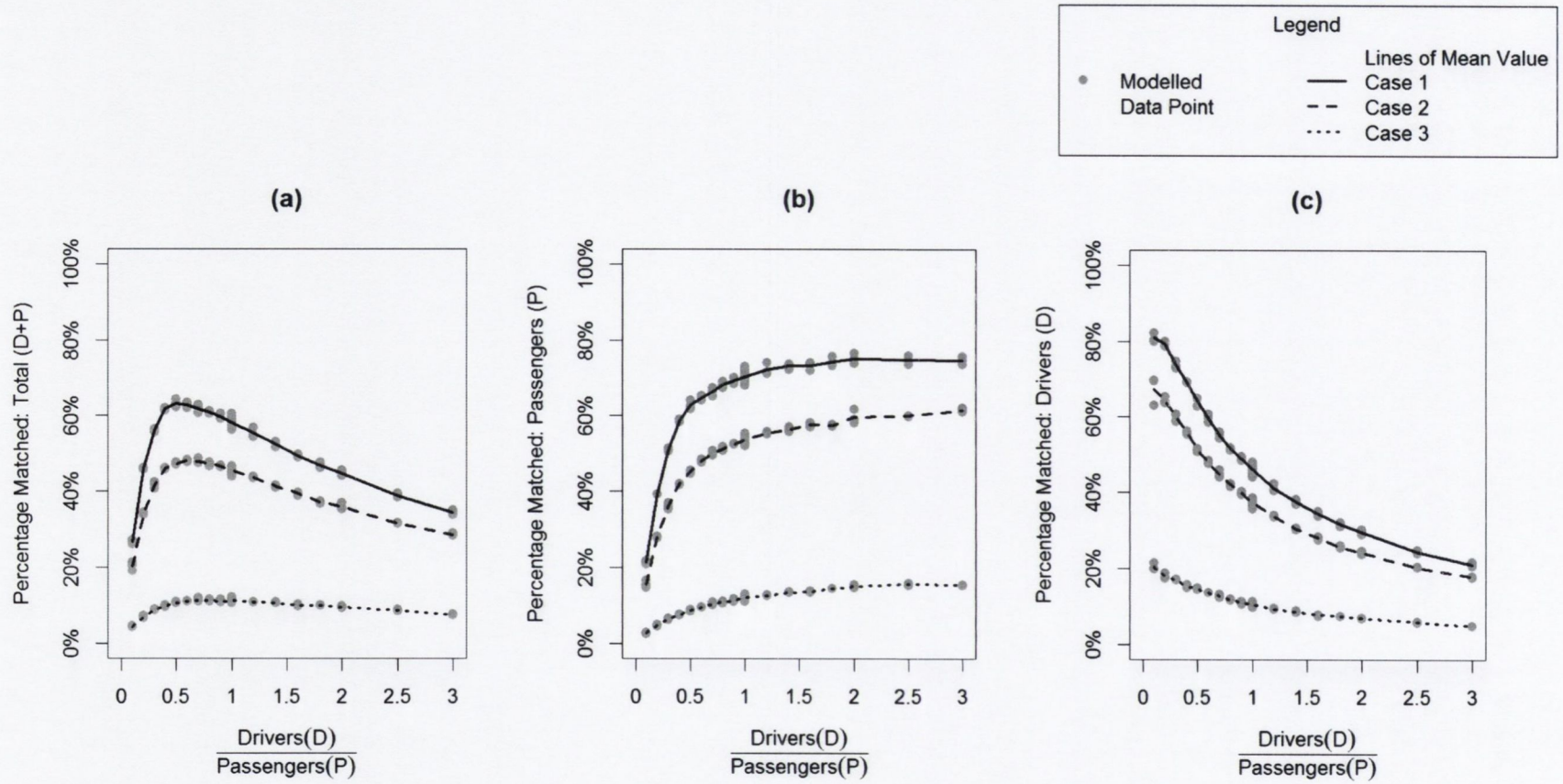

Figure 6.18: Impact of Varying Driver to Passenger Ratio (D/P) for (a) All Matches, (b) Passenger Matches and (c) Driver Matches

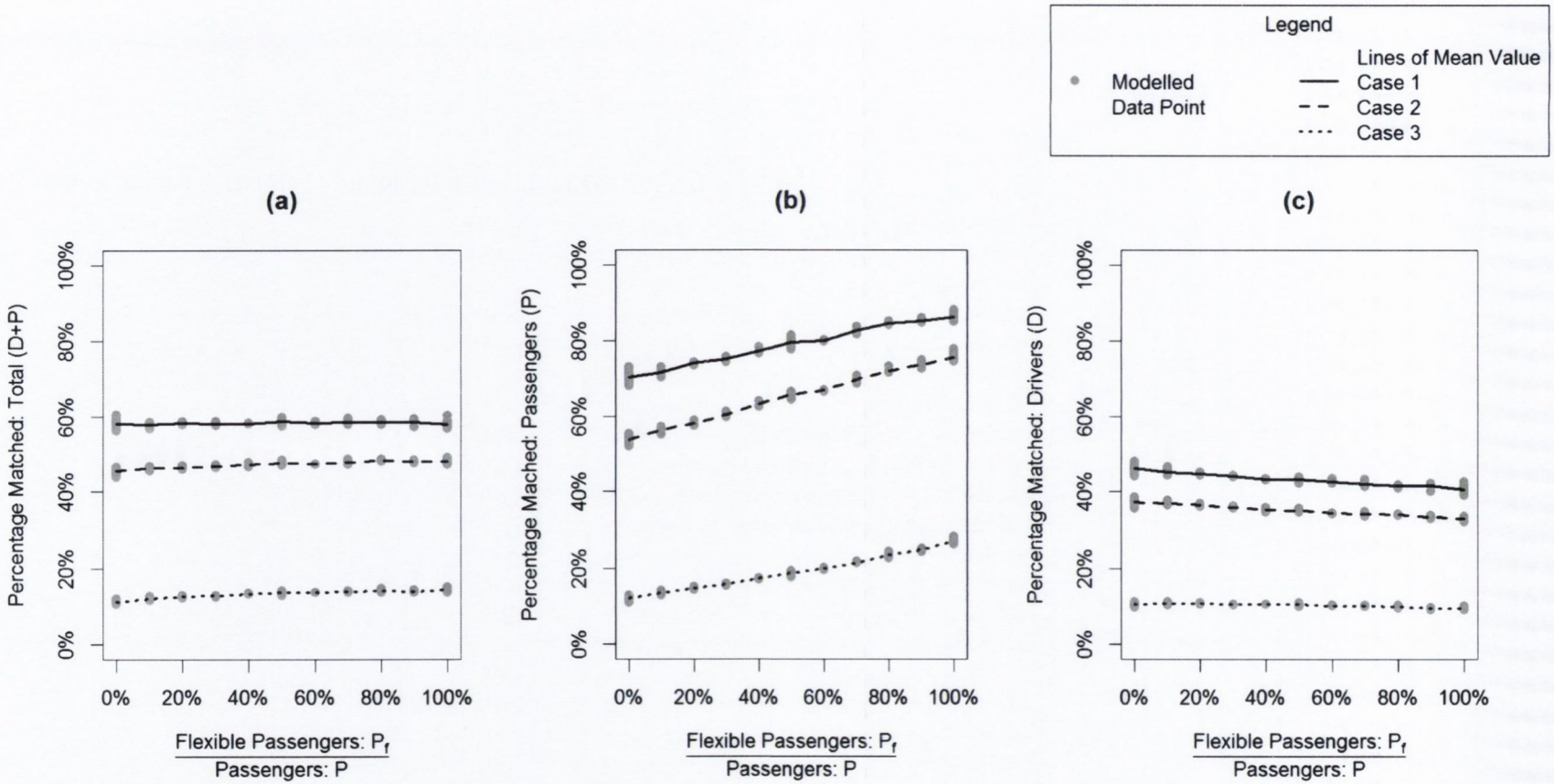

Figure 6.19: Impact of Varying Proportion of Flexible Passengers (P_f/P) for (a) All Matches, (b) Passenger Matches and (c) Driver Matches

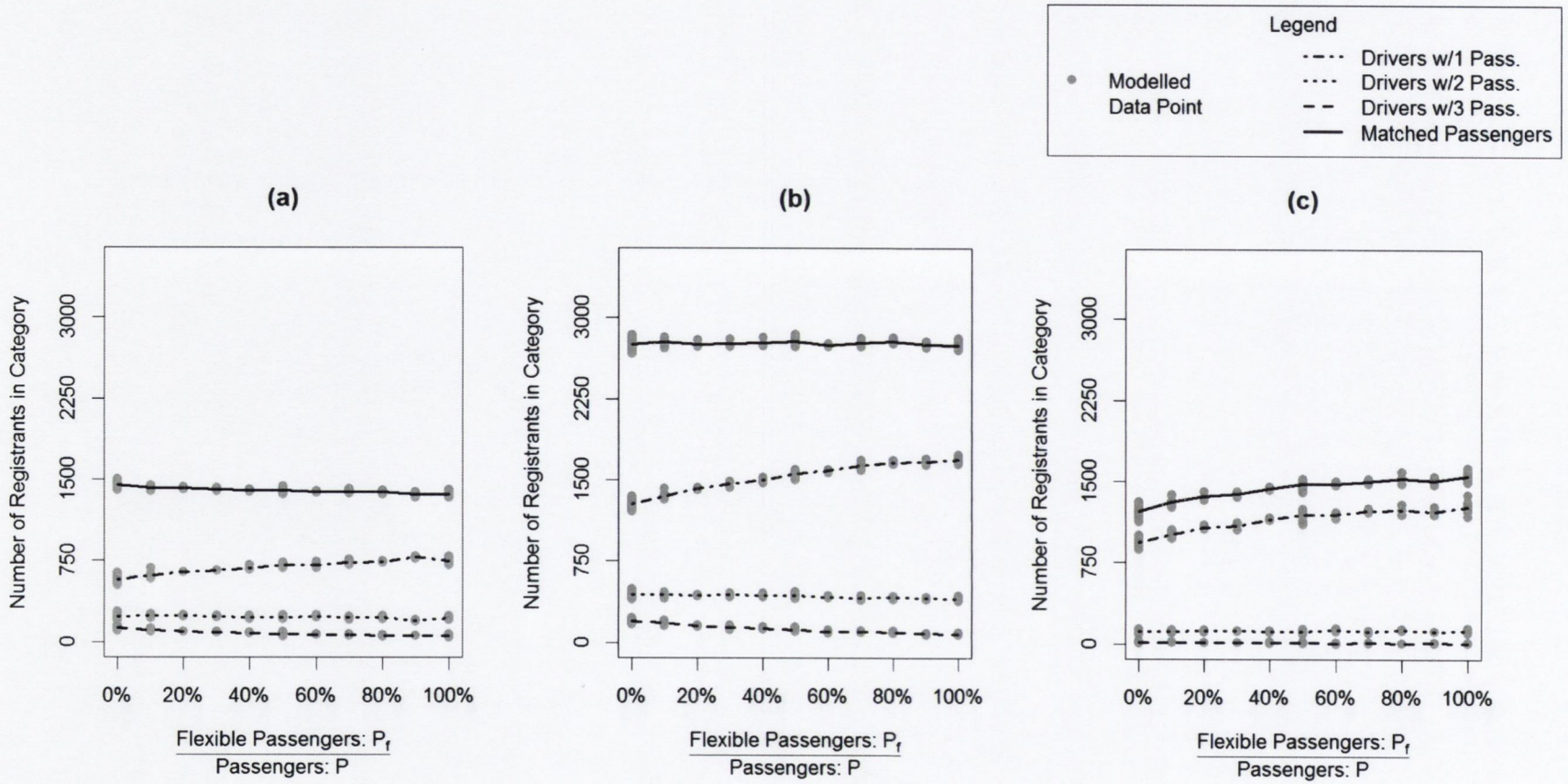

Figure 6.20: Absolute Impact of Varying P_f/P for (a) Case 1, (b) Case 2 and (c) Case 3

6.6.2 Flexible Registrants

In this second stage of analysis, the ratio of Drivers to Passengers is again maintained at 1 (D/P = 1), and the impact of allowing a proportion of those registering later to seek matches as either a driver or a passenger is examined. Where "Passengers", or P are referred to in this and following sections, it includes those who register seeking matches only as a Passenger (P_i) and those who register seeking matches as a driver or a passenger (P_f). Where flexible individuals (P_f) remain unmatched, they are recorded as an unmatched passenger and excluded from the driver results.

Figure 6.19 presents the results of varying the proportion of passengers who register flexibly (P_f/P) when the number of drivers equals the number of passengers ($D=P_f+P_i$). The analysis appears to show that as the proportion of flexible registrants (P_f) increases, the proportion of passengers achieving a match increases while the proportion of drivers achieving a match falls, resulting in no overall impact. However, in the results of this analysis the number of registrants acting as passengers and drivers is varying as flexible passengers are added to the driver pool from the passenger pool. The results of each case are therefore also presented in terms of the number of registrants in Figure 6.20, with Case 1 presented in Figure 6.20 (a), Case 2 presented in Figure 6.20 (b) and Case 3 presented in Figure 6.20 (c).

Figure 6.20 shows that a complex interaction takes place regarding the number of passengers carried by each driver. When flexible registrants are introduced, fewer drivers carry two or three passengers, while the number of drivers carrying exactly one passenger increases. The variation in the slopes of the lines in cases 1, 2 and 3 also suggests a further interaction with the number of registrants, the constraints applied and the proportion of flexible registrants. In particular for Case 3 (Figure 6.20 (c)), which has the narrowest constraints, both the number of passengers matched and the number of drivers matched increases.

In all the presence of flexible registrants alters the outcome of the model in terms of the match rates achieved for specific roles, however when the number of drivers is equal to the number of passengers and flexible registrants, the overall impact is small. The next section examines how the results change when both D/P and P_f/P are varied simultaneously.

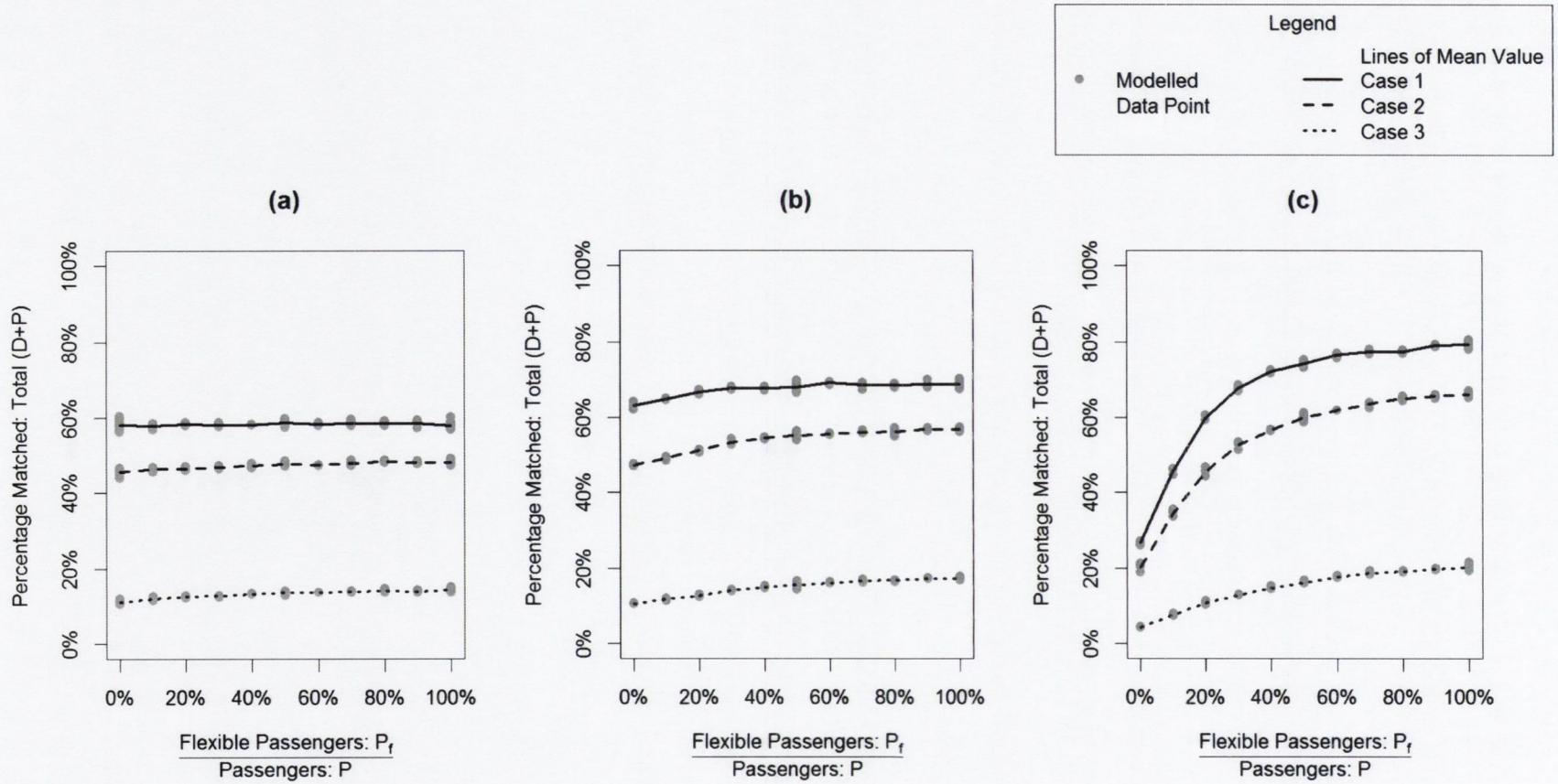

Figure 6.21: Proportion of Registrants achieving matches at (a) D/P =1, (b) D/P = 0.5 and (c) D/P=0.1

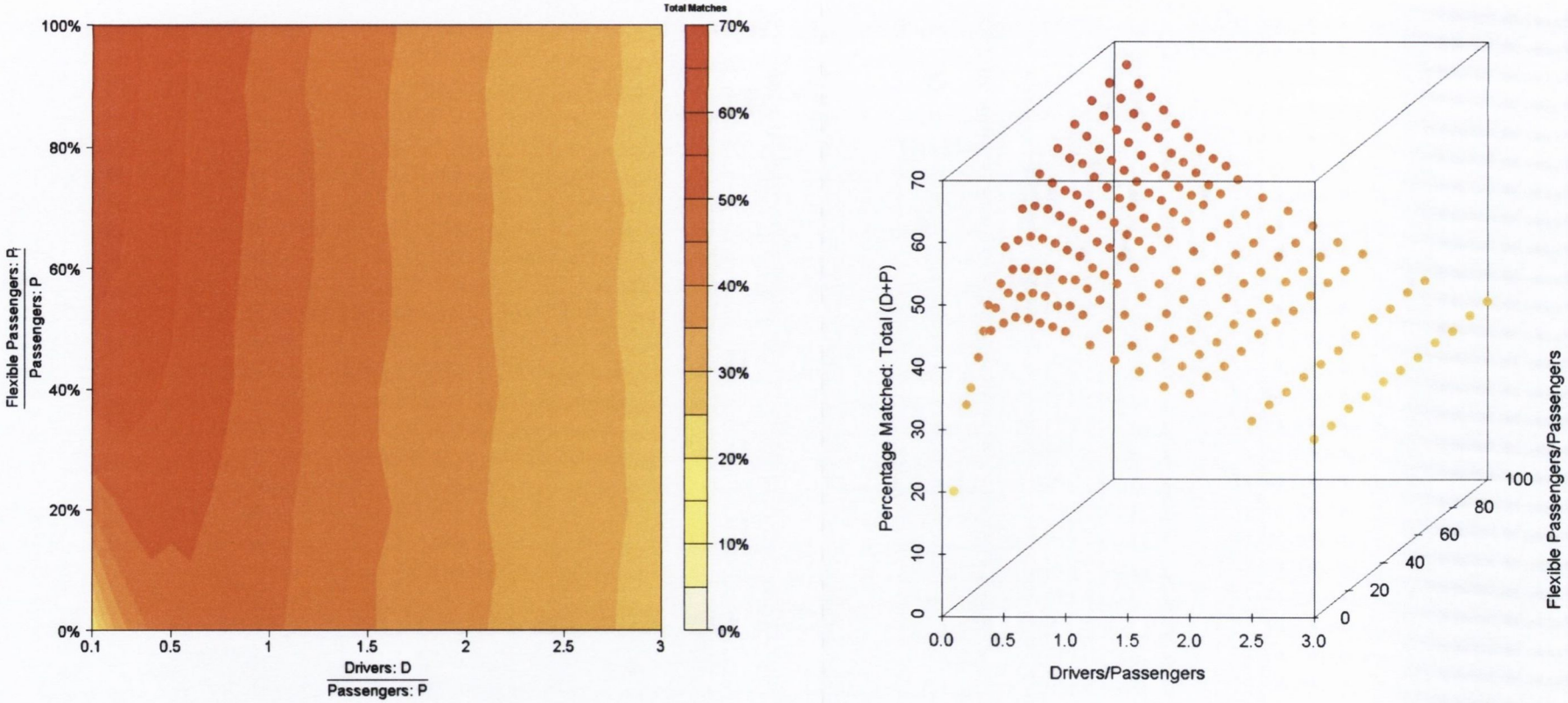

Figure 6.22: FMA Contour Plot and 3d Plot showing interaction between Driver:Passenger Ratio (D/P) and Proportion of Flexible Registrants (P_f/P) under Case 2 when each driver has 3 Seats available to passengers.

Note: Both graphs show the same data, the 3d plot is provided to aid understanding of how the changing ratios affect the match rate, while the contour plot is provided to enable the reader to identify the match rate for specific combinations of ratios.

6.6.3 Driver to Passenger Ratio and Flexible Passenger Interaction

It appeared in the analysis presented in the previous section that allowing registrants to register flexibly offers little benefit, however on further analysis, this conclusion was found to be incorrect. Flexible registrants can offer a considerable increase in successful matching, however this increase is only realised when the ratio of Drivers to Passengers falls below 1, i.e. there is a shortage of available drivers.

Figure 6.21 (a) illustrates the case discussed in section 6.6.2, where a small increase in the proportion of registrants matched was detected in Case 3, and no change was detected for Case 1 or 2. Figure 6.21 (b) and Figure 6.21 (c) then illustrate how the proportion of flexible registrants influences the match rate as D/P is reduced; first to 0.5 (Figure 6.21 (b)) and then to 0.1 (Figure 6.21 (c)). Together these show that when the number of drivers is reduced and the number of flexible passengers is increased, a considerable increase in the proportion of registrants achieving a match can be obtained.

Figure 6.22 provides a contour plot and a 3d Plot of Case 2. This further illustrates the high match rates achieved when the number of registrants seeking matches solely as drivers is low and the number of registrants in the flexible category is high. Taking Case 2 as an example, per Table 6.3 we expect a match rate of 45.7% when D=P (D/P=1) and no passengers take the flexible role. As illustrated in Figure 6.21 (c) When 932 registrants seek matches only as a driver and the remaining 9320 registrants seek matches as both a driver and passenger (D/P=0.1, P_f/P=1) a match rate of 66.3% is achieved.

6.6.4 Number of Seats

In analysing the influence of flexible registrants in section 6.6.2 a clear interaction between match rates and the number of passengers carried by each driver was identified. A better understanding of this interaction was therefore sought. The impact of both a 1 passenger/driver and a 2 passenger/driver limit were explored.

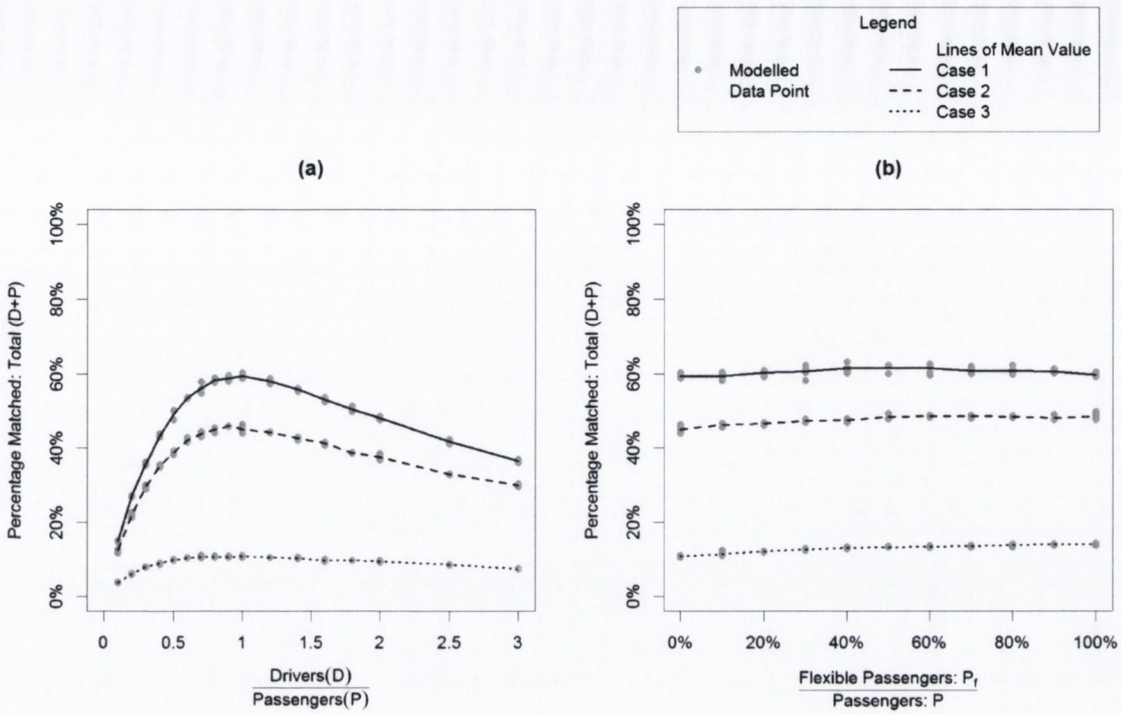

Figure 6.23: Driver Seat Capacity of 1 and (a) Driver to Passenger Ratio and (b) Proportion of P_f

A limit of 2 passengers/driver was found to produce match rates virtually identical to those of 3 passengers/driver, therefore only the results of the 1 passenger/driver case are therefore illustrated here. Figure 6.23 (a) can be compared with Figure 6.18 (a). The pattern of change to the match rate is similar in both graphs; however with the reduced driver capacity, the peak match rate occurs when the driver to passenger ratio is 1 (i.e. D/P=1). Figure 6.23 (b) showing the influence of flexibility in matching can be compared with Figure 6.19 (a), and again the pattern of change when flexible passengers are introduced to the model is similar to that for a seat capacity of 3.

Figure 6.24 explores the interaction of Driver to Passenger Ratio and the proportion of flexible passengers for Case 2 when each driver has a seat capacity of 1. It can be compared to Figure 6.22. The pattern of changing match rate exhibited is very similar to that found in section 6.6.3, i.e. when D/P is reduced and P_f/P increased, an increased match rate is found. The benefit of reducing D/P and increasing P_f/P is lessened when drivers have a seat capacity of 1. The peak match rate achieved (at D/P=0.1, P_f/P=1) is 62%, vs the 66% achieved with 3 seats.

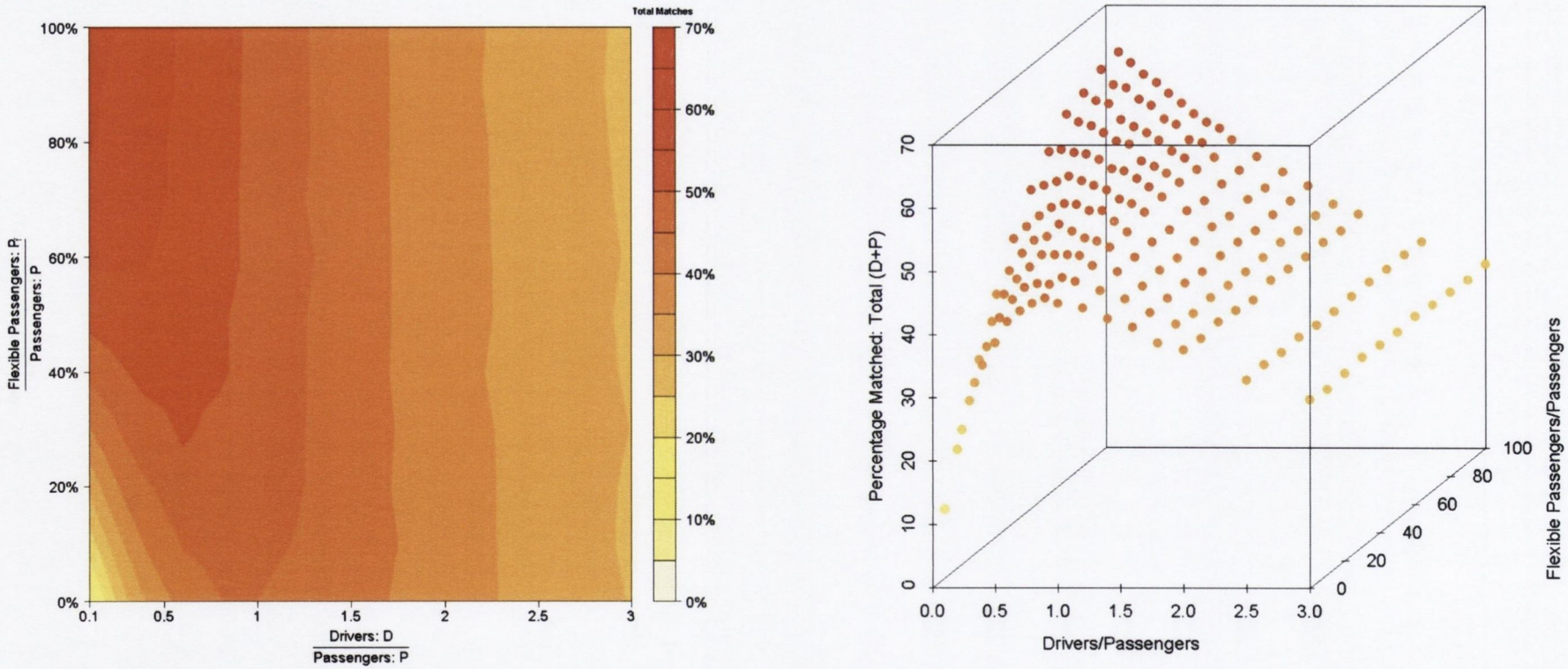

Figure 6.24: FMA Contour Plot and 3d Plot showing interaction between Driver:Passenger Ratio and Proportion of Flexible Registrants, when each driver has one seat available to passengers.

Note: Both graphs show the same data, the 3d plot is provided to aid understanding of how the changing ratios affect the match rate, while the contour plot is provided to enable the reader to identify the match rate for specific combinations of ratios.

6.7 Model 3: Social Matching Algorithm

In this model, the algorithm is modified to illustrate the possible effects of personal preferences on match rates. Three potential areas of personal preference for match partners are considered – Age, Gender and Socio-Economic Group. As described in section 6.3.4, a scale is assigned to each variable and the algorithm uses these scales to calculate a social difference for each pair of matched registrants. As outlined in section 6.3.4, based on this social difference and a chance parameter the match is more or less likely to be accepted. In the analyses described in this section we vary the chance parameter between 0.5 and 1 and present the analysis of the resulting changes in match rate.

Throughout this section we again use the three base cases described in section 6.6, and for each of the three cases we examine three possible levels of flexibility. These are:

A. $D/P = 1$, $P_f/P = 0$: This ratio is that same as the base case results
B. $D/P = 0.5$, $P_f/P = 0.5$
C. $D/P = 0.1$, $P_f/P = 1$

In terms of proportion of registrants, this means that under Case A, 50% of registrants register as D_j and 50% of registrants register as P_i; under Case B 33% of registrants register as D_j, 33% of registrants register as P_i and 33% of registrants register as P_f; and under Case C 9% of registrants register as D_j and 91% of registrants register as P_f. The expected results for Case A are the same as those presented in Table 6.3. The expected results for Case B are presented in Table 6.4 and the expected results for Case C are presented in Table 6.5.

Figure 6.25 illustrates the change in the match rates achieved when the model of individual preferences is applied. As expected, when people are more reluctant to share journeys with dissimilar individuals, the match rate falls. The fall in match rate is similar for each of the cases examined and it therefore appears that there is no interaction between the influence of social matching and the other constraints applied. Figure 6.26 examines the three components of the social matching algorithm independently, using Case B to illustrate the variation. The influence of each of the three components is consistent with the scales used to calculate the SD variable, e.g. the gender variable has a maximum difference of 2 and consequently the reduction in match rate is smaller.

Table 6.4: Expected Results for Case 1, 2 & 3 when D/P = 0.5 and $P_f/P = 0.5$

	Case 1				Case 2				Case 3			
			95% Conf Int.				95% Conf Int.				95% Conf Int.	
	Mean	St. Dev	Upper	Lower	Mean	St. Dev	Upper	Lower	Mean	St. Dev	Upper	Lower
Drivers												
Unmatched	791.0	20.5	804.8	777.2	2541.6	30.5	2559.3	2524.0	8699.3	50.6	8702.4	8696.2
Matched	1089.9	47.6	1121.9	1057.9	2279.6	76.3	2323.6	2235.5	1467.5	49.7	1470.6	1464.4
Drivers w/1 Passenger	*632.7*	*27.0*	*650.9*	*614.6*	*1443.9*	*41.7*	*1467.9*	*1419.8*	*1254.6*	*31.8*	*1256.5*	*1252.6*
Drivers w/2 Passengers	*299.0*	*10.3*	*305.9*	*292.1*	*578.2*	*21.4*	*590.6*	*565.9*	*181.7*	*12.5*	*182.5*	*181.0*
Drivers w/3 Passengers	*158.2*	*10.4*	*165.1*	*151.2*	*257.5*	*13.2*	*265.1*	*249.9*	*31.2*	*5.4*	*31.5*	*30.8*
Passengers												
Unmatched	514.8	15.9	525.5	504.1	2057.0	38.6	2079.3	2034.7	8624.6	52.0	8627.8	8621.4
Matched	1705.3	17.0	1716.7	1693.9	3372.8	31.0	3390.7	3354.9	1711.6	37.7	1713.9	1709.3
Match Rates												
Passengers	76.8%	51.6%	76.6%	77.1%	62.1%	44.5%	62.0%	62.2%	16.6%	42.0%	16.6%	16.5%
Drivers	57.9%	69.9%	58.2%	57.6%	47.3%	71.4%	47.6%	47.0%	14.4%	49.6%	14.5%	14.4%
Total	68.2%	63.9%	68.1%	68.2%	55.1%	60.8%	55.2%	55.1%	15.5%	46.0%	15.5%	15.5%

Table 6.5: Expected Results for Case 1, 2 & 3 when D/P = 0.1 and $P_f/P = 1$

	Case 1				Case 2				Case 3			
			95% Conf Int.				95% Conf Int.				95% Conf Int.	
	Mean	St. Dev	Upper	Lower	Mean	St. Dev	Upper	Lower	Mean	St. Dev	Upper	Lower
Drivers												
Unmatched	501.9	17.0	515.0	488.8	1975.6	44.8	2004.1	1947.1	8957.2	38.1	8986.5	8927.9
Matched	1206.1	45.2	1240.8	1171.4	2645.4	86.6	2700.4	2590.4	1850.8	65.1	1900.8	1800.8
Drivers w/1 Passenger	*602.8*	*24.3*	*621.5*	*584.1*	*1502.0*	*40.2*	*1527.5*	*1476.5*	*1461.7*	*36.1*	*1489.4*	*1433.9*
Drivers w/2 Passengers	*372.2*	*6.7*	*377.4*	*367.0*	*785.3*	*28.8*	*803.5*	*767.0*	*335.6*	*22.5*	*352.8*	*318.3*
Drivers w/3 Passengers	*231.1*	*14.1*	*242.0*	*220.2*	*358.2*	*17.6*	*369.3*	*347.0*	*53.6*	*6.5*	*58.5*	*48.6*
Passengers												
Unmatched	352.4	16.7	365.3	339.6	1483.0	38.7	1507.6	1458.4	7401.6	73.0	7457.7	7345.4
Matched	2040.6	29.3	2063.0	2018.1	4147.0	35.5	4169.6	4124.4	2293.4	43.3	2326.8	2260.1
Match Rates												
Passengers	85.3%	63.7%	85.0%	85.6%	73.7%	47.9%	73.4%	73.9%	23.7%	37.2%	23.8%	23.5%
Drivers	70.6%	72.6%	70.7%	70.6%	57.2%	65.9%	57.4%	57.1%	17.1%	63.1%	17.5%	16.8%
Total	79.2%	68.8%	79.0%	79.4%	66.3%	59.4%	66.2%	66.3%	20.2%	49.4%	20.5%	20.0%

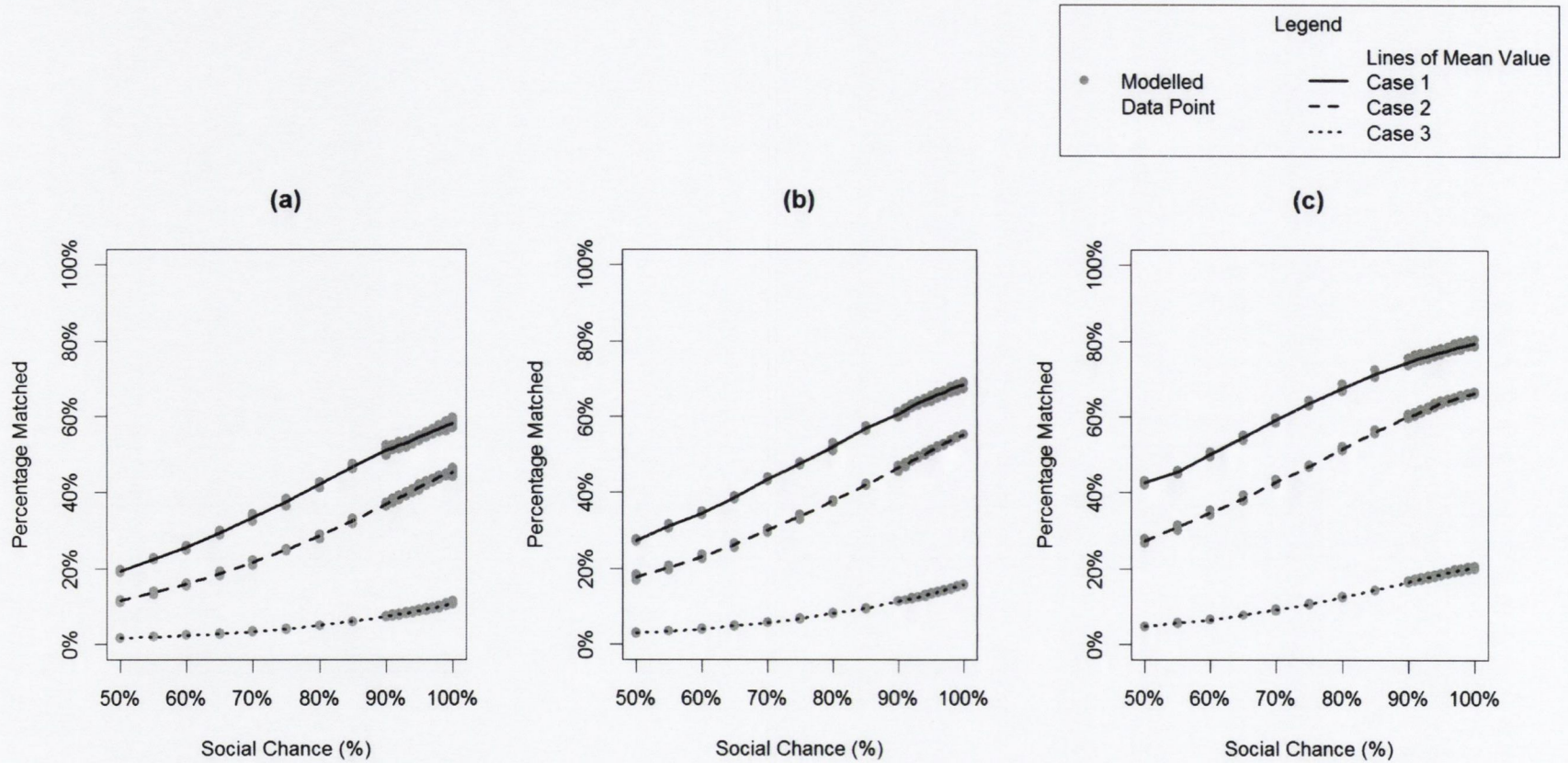

Figure 6.25: Impact of Personal Preferences on Match Rate for (a) Case A, (b) Case B and (c) Case C

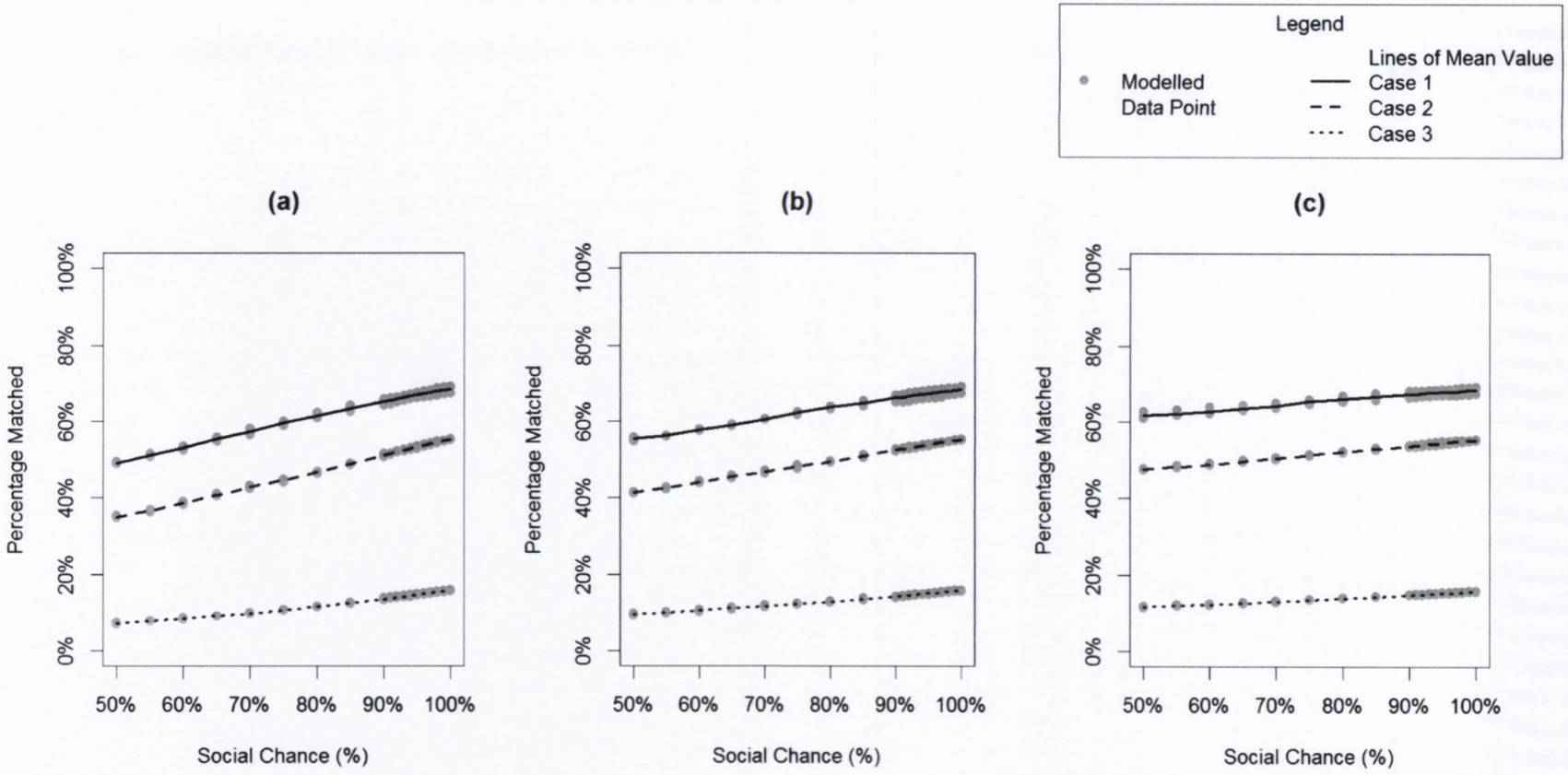

Figure 6.26: Impact of (a) Age, (b) Socio-Economic Group and (c) Gender on match rates using Case B

6.8 Model 4: Dynamic Matching Algorithm

This algorithm represents a dynamic model, i.e. the details of all registrants are not known at the start of the matching process. It therefore differs considerably from the three models previously described. In the analysis of the model, three parameters are varied. These are the proportion of drivers registering before the start of matching (ID_j/D), the number of batches in which new registrants are matched (NB), and the proportion of unmatched passengers whose details are retained and carried forward for matching with the next batch of newly registering users (RR).

We examine each of the three parameters (NB, ID_j/D, RR) in turn. Each of these three parameters is intrinsically linked with the other two. For instance the effect of changes in the Retention Rate (RR) and the proportion of initial drivers (ID) is related to the number of batches. When there is only one batch, the solution to the model is identical to that considered under the FMA.

Throughout this analysis we utilise the same cases 1, 2 & 3 a described in section 6.6 and variations in registrant flexibility as described in section 6.7 (i.e. Case A, B & C). Since the symbols used to describe each category of passenger has changed, the equations used to calculate equivalent values of D, P, P_f/P and D/P in this section are provided in Equation 6.11 below.

Equation 6.11: Calculation of Model Properties under the DMA: (a) Number of Drivers, (b) Number of Passengers, (c) Pf/P, (d) D/P and (e) Proportion of Initial Drivers

$$D = ID_j + (B_j * NB) \qquad 6.11\ (a)$$

$$P = (B_i + B_f) * NB \qquad 6.11\ (b)$$

$$\frac{P_f}{P} = \left(\frac{B_f}{B_f + B_i} \right) \qquad 6.11\ (c)$$

$$\frac{D}{P} = \frac{ID_j + (B_j * NB)}{(B_i + B_f) * NB} \qquad 6.11\ (d)$$

$$\text{Proportion of Initial Drivers} = \frac{ID_j}{D} \qquad 6.11\ (e)$$

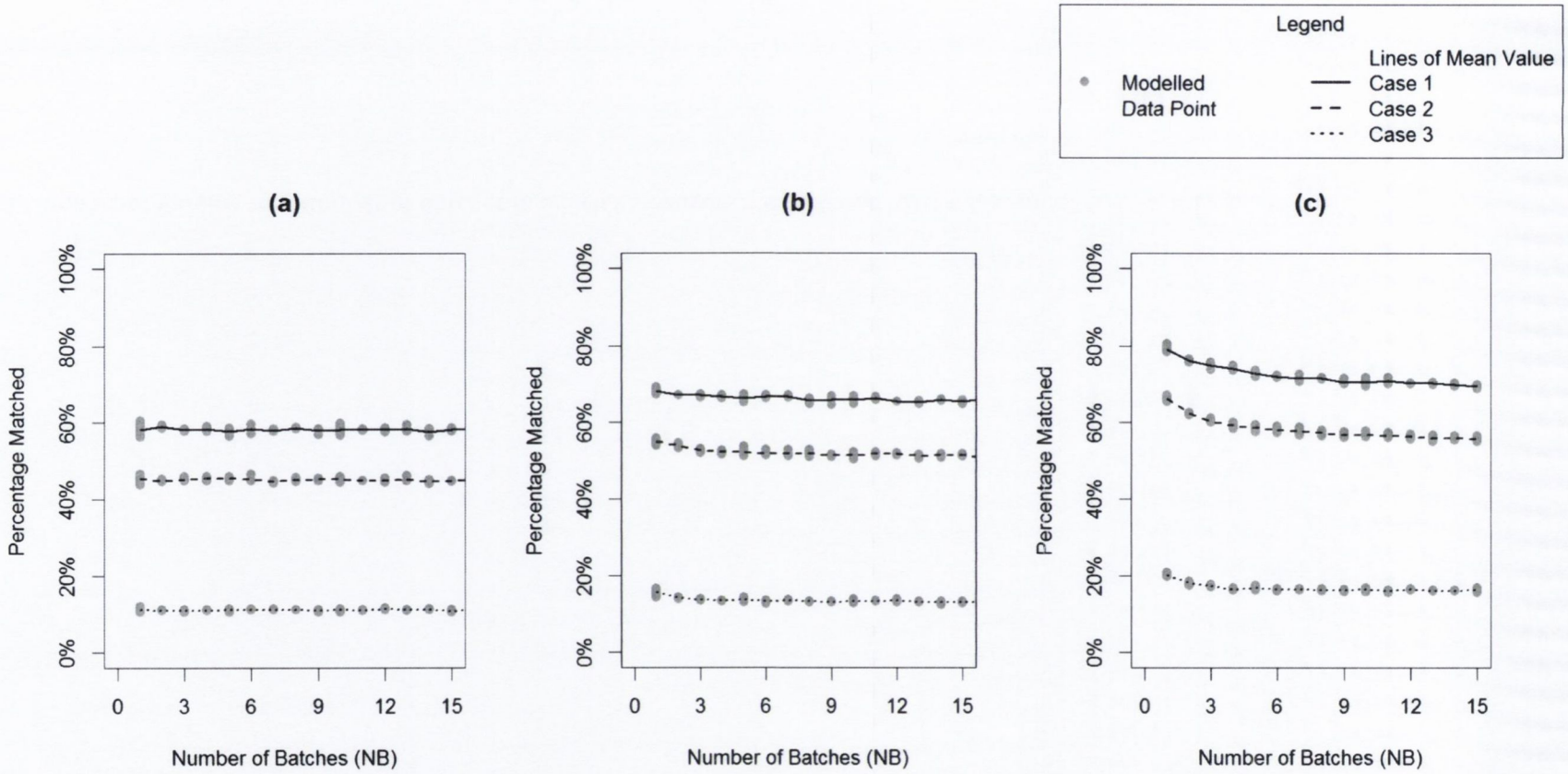

Figure 6.27: Impact of Varying the Number of Batches in which Passengers are Matched ID/D = 1 for (a) Case A, (b) Case B and (c) Case C

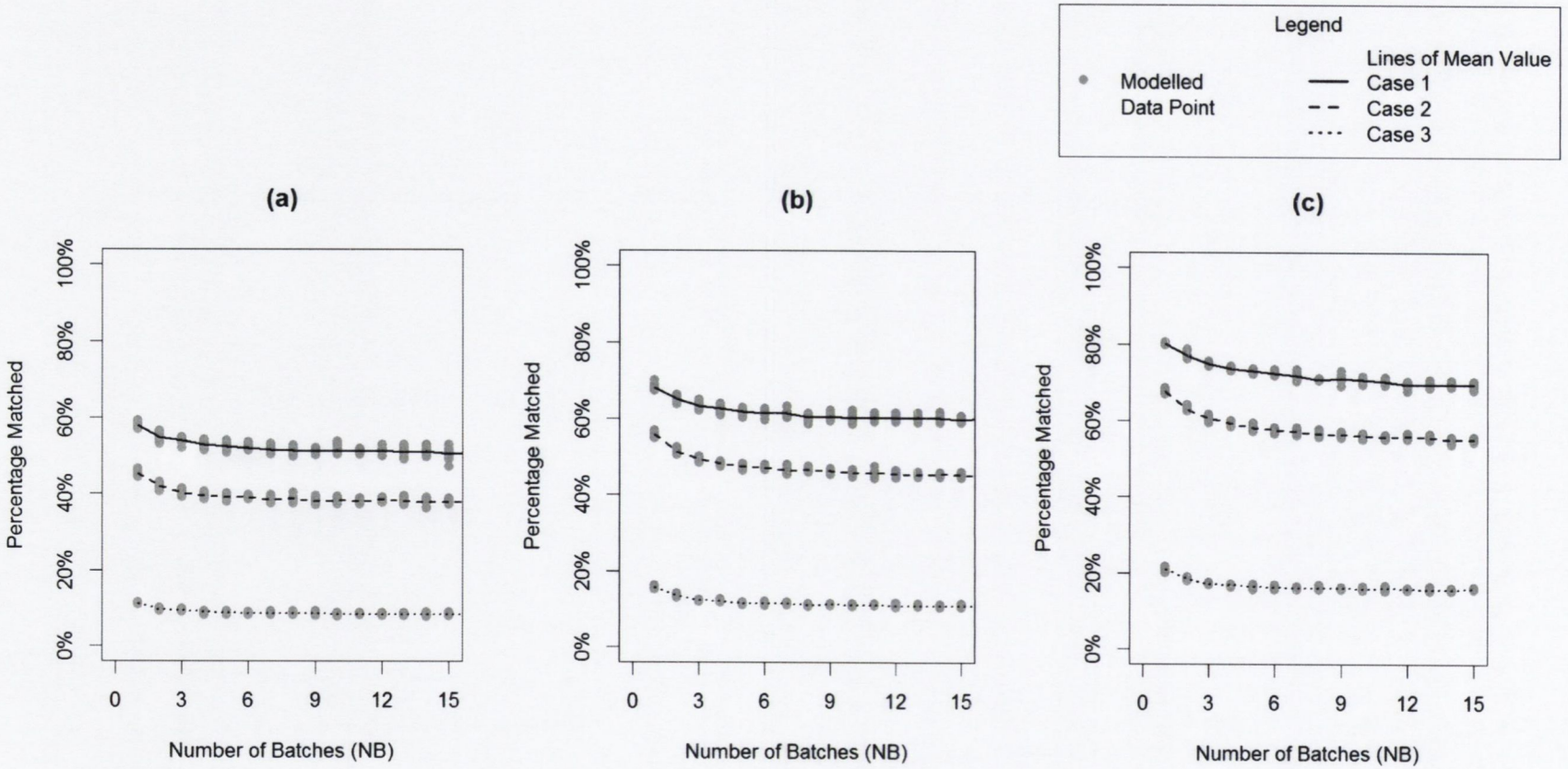

Figure 6.28: Impact of Varying the Number of Batches in which Passengers are Matched ID/D = 1/3 for (a) Case A, (b) Case B and (c) Case C

6.8.1 Number of Batches

This section explores how the number of batches affects the match rate. Throughout this analysis the RR is set at 0%. In Figure 6.27 we show how the match rate varies as the number of batches of drivers increase. In this figure no individuals B_j register with the batches, i.e. all those seeking matches exclusively as a driver register as ID_j before the start of the matching process. When there are no flexible registrants, as in Figure 6.27 (a), the use of batches has no impact on the match rate. This is expected since in this scenario, all drivers are registered and available as a match before any passengers register. When fewer exclusive drivers (ID_j and B_j) register and registrants are flexible (B_f) about the roles they undertake, we see the batching process have an impact on the match rates. This is illustrated in Figure 6.27 (b) and (c) and the effect can be seen most clearly in Figure 6.27 (c) when the number of batches is above ten. In this scenario, those registering in the first batches have very few drivers (either ID_j or B_f) available to them and consequently these passengers (either B_i or B_f) do not find matches.

In Figure 6.28 we use Equation 6.11 (e) and reduce the proportion of initial drivers to 33% of the total number of exclusive drivers (D). The remaining exclusive drivers join the RSS within batches as B_j. When the number of initial drivers (ID_j) is decreased, this means fewer drivers are available to the first batches of registrants. Therefore when ID_j is reduced, the use of batches has a greater impact and the match rate reduces across all cases. However across all cases the reduction in match rate is relatively small when compared to the gains made via the introduction of flexible registrants This can be clearly seen by comparing Case A with no flexible registrants (Figure 6.28 (a)) to Case C which has 90% flexible registrants (Figure 6.28 (c)). Match rates at 15 batches under Case C (Figure 6.28 (c)) exceed those for 1 batch under Case A (Figure 6.28 (a)).

Overall the use of batches can be said to have a negative impact which is mitigated by an increased availability of drivers in the early stages. The increased availability of drivers may be a result of registrants seeking matches exclusively as drivers or in the flexible role.

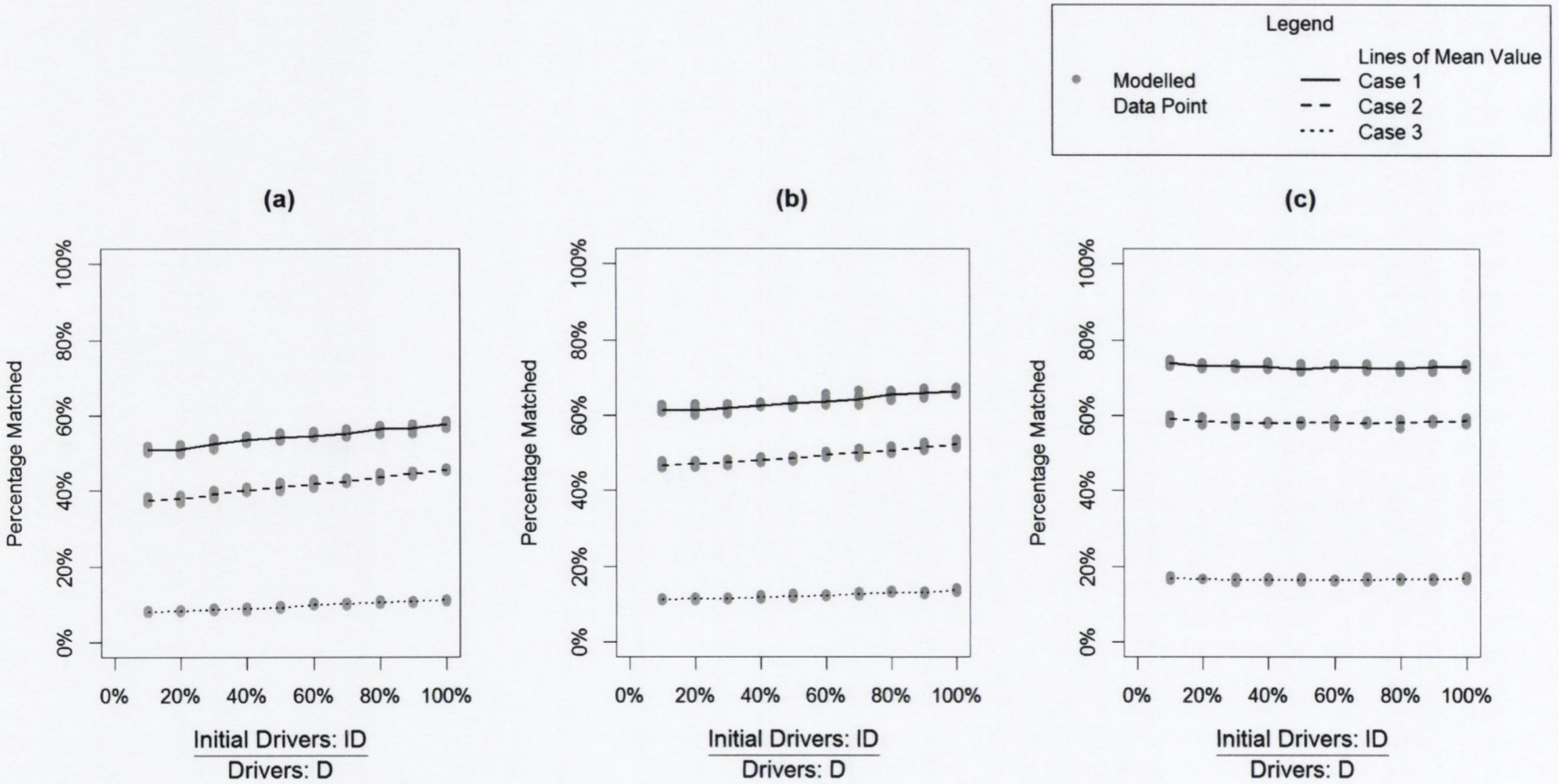

Figure 6.29: Impact of Varying Initial Drivers, Number of Batches = 5 for (a) Case A, (b) Case B and (c) Case C

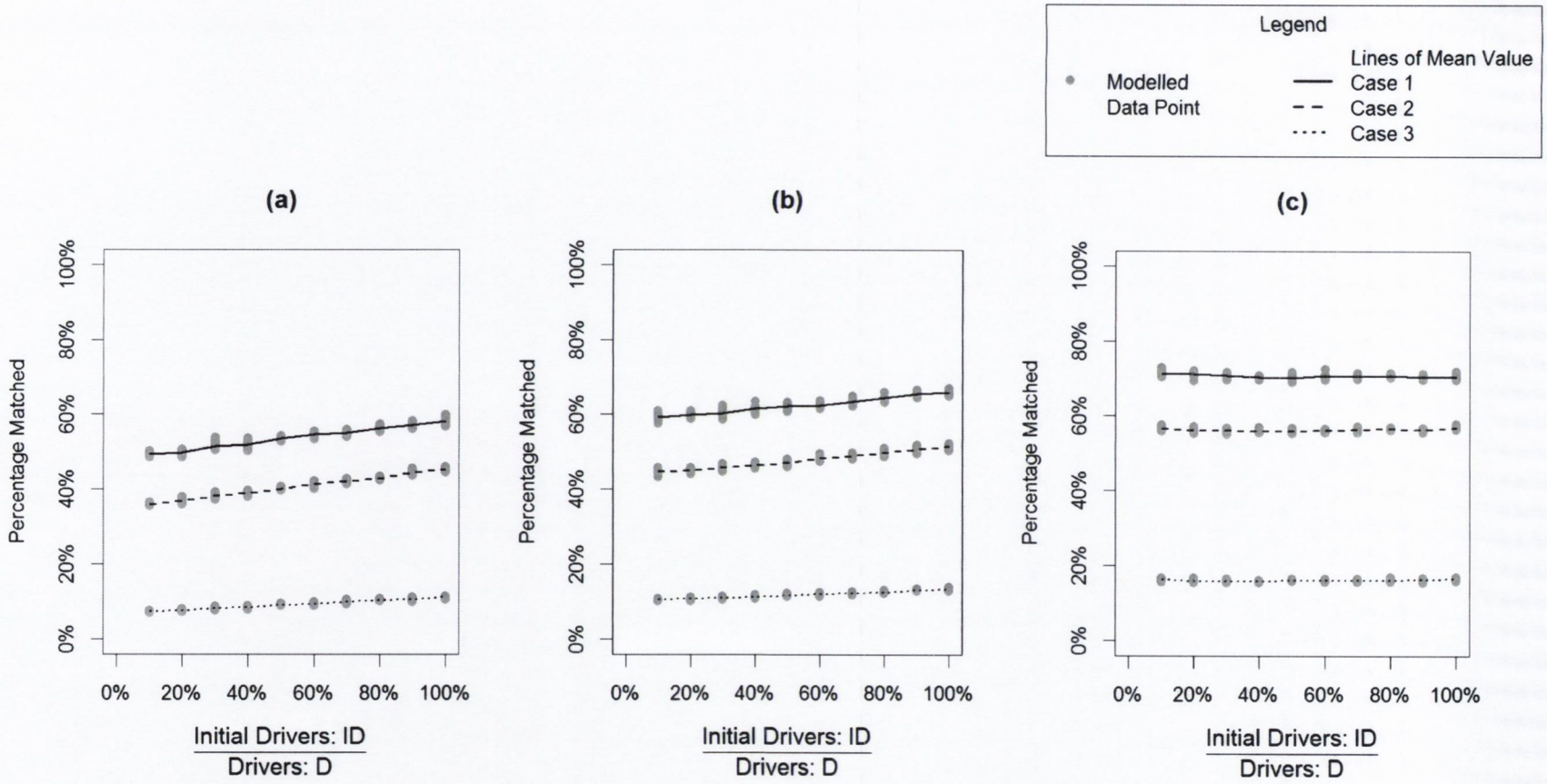

Figure 6.30: Impact of Varying Initial Drivers, Number of Batches = 10 for (a) Case A, (b) Case B and (c) Case C

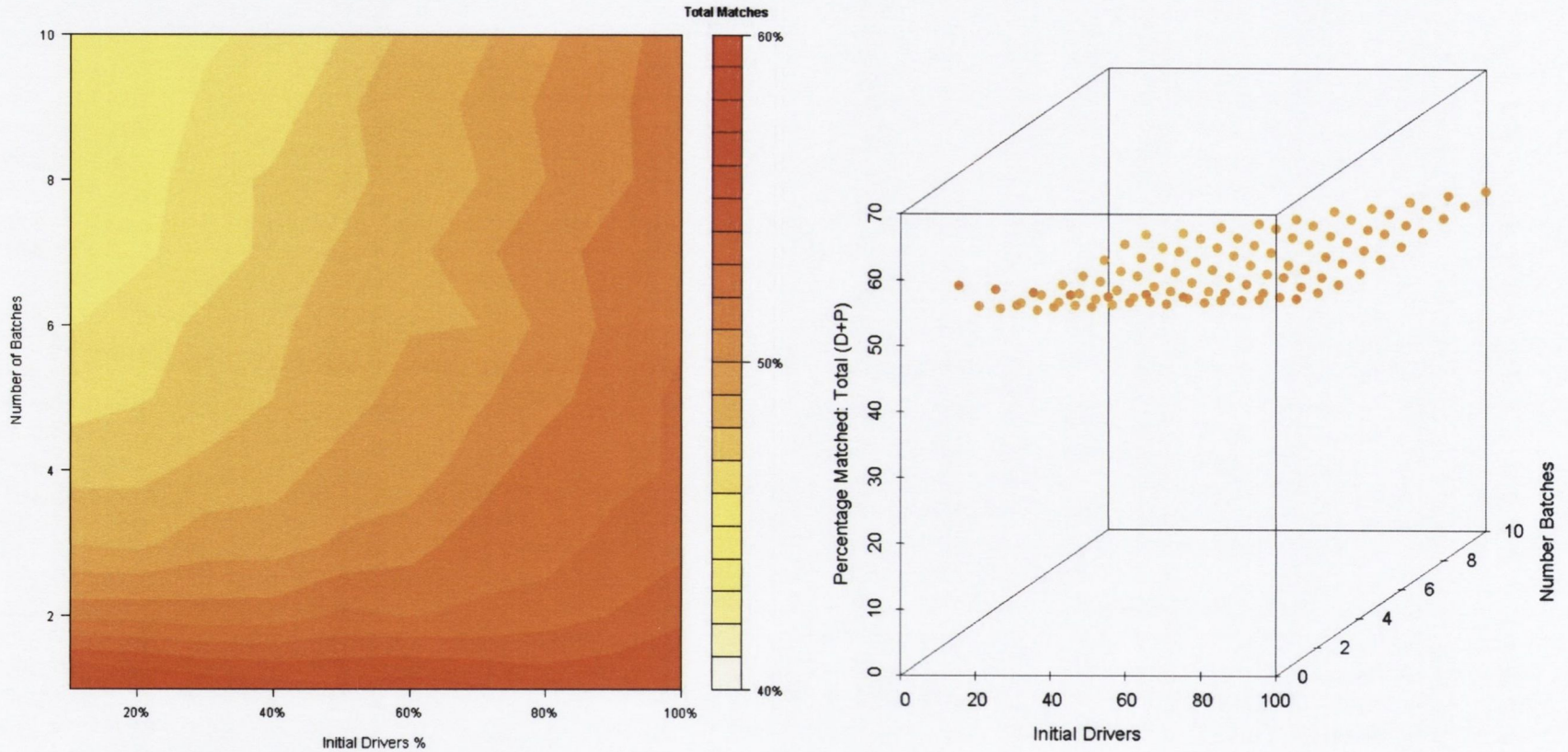

Figure 6.31: Case 2 B – Contour Plot showing relationship between Number of Batches and Proportion of Initial Drivers at Retention Rate=0%

6.8.2 Initial Drivers

In this section we further explore the impact of reducing the number of initial drivers (ID_j) as a proportion of the total number of drivers (D). The RR is set at 0% throughout. Since a change in ID_j has no effect unless registrants arrive in a number of batches, we illustrate the results by presenting Figure 6.29 where ID_j is varied and 5 batches of registrants arrive and Figure 6.30 where ID_j is varied and 10 batches of registrants arrive.

In Case A (Figure 6.29 (a), Figure 6.30 (a)) and Case B (Figure 6.29 (b), Figure 6.30 (b)) 50% and 33% of the registrants respectively seek matches exclusively as drivers. When these drivers are not registered before the start of the matching process (they join as B_j instead of as ID_j), a significant reduction in the match rate is found. As Case C (Figure 6.29 (c), Figure 6.30 (c)) illustrates, when more registrants adopt a flexible role (B_f) this effect is mitigated.

Figure 6.31 provides a contour plot and 3d plot for Case 2 B when the retention rate is zero. It clearly illustrates the pattern of effect on the match rate which varying the number of batches and the proportion of Initial Drivers produces. When there is one batch, or 100% initial drivers, the impact of variations in the other parameter is minimal. When the proportion of initial drivers is reduced to 10% and the number of batches is increased to 10, we see the maximum effect on the match rate, in this case a reduction of 10% from the peak of 57% (at 1 batch and 100% ID_j).

These findings reinforce the findings in section 6.8.1. That is that having a pre-registered pool of drivers available prior to the start of matching increases the match rate and mitigates the effect of batching.

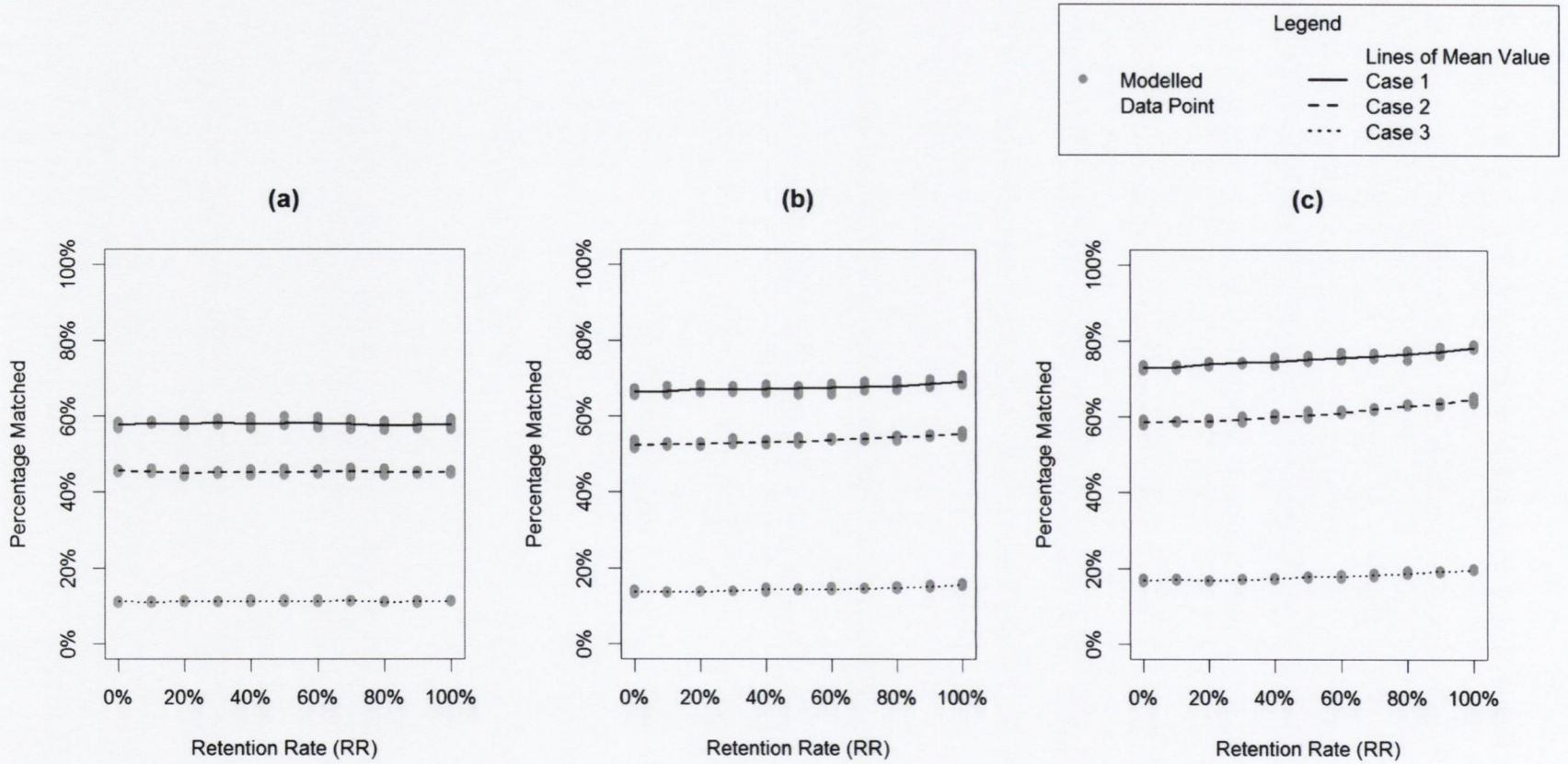

Figure 6.32: Variation in Retention Rate with 5 Batches and 100% Initial Drivers for (a) Case A, (b) Case B and (c) Case C

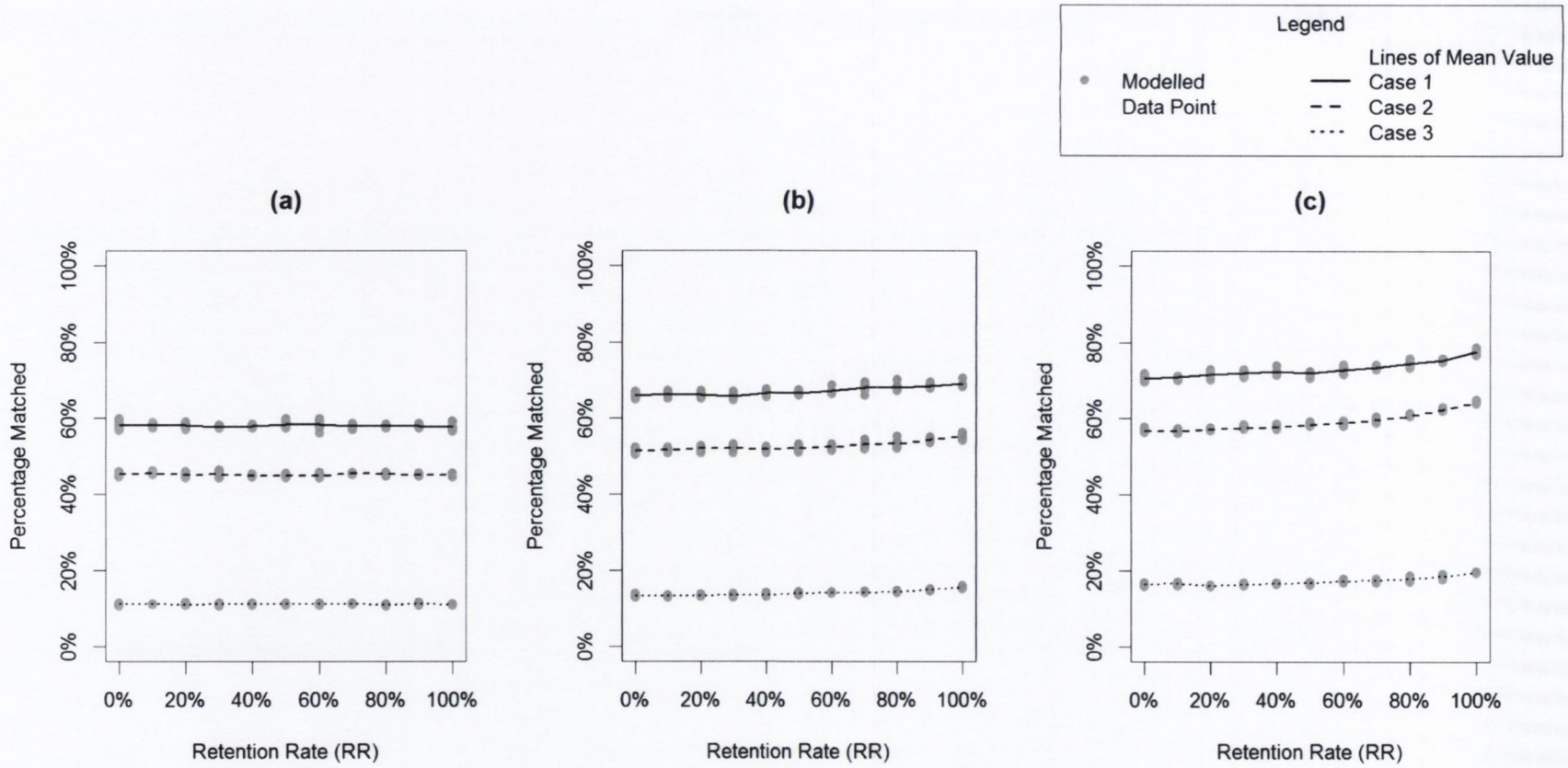

Figure 6.33: Variation in Retention Rate with 10 Batches and 100% Initial Drivers for (a) Case A, (b) Case B and (c) Case C

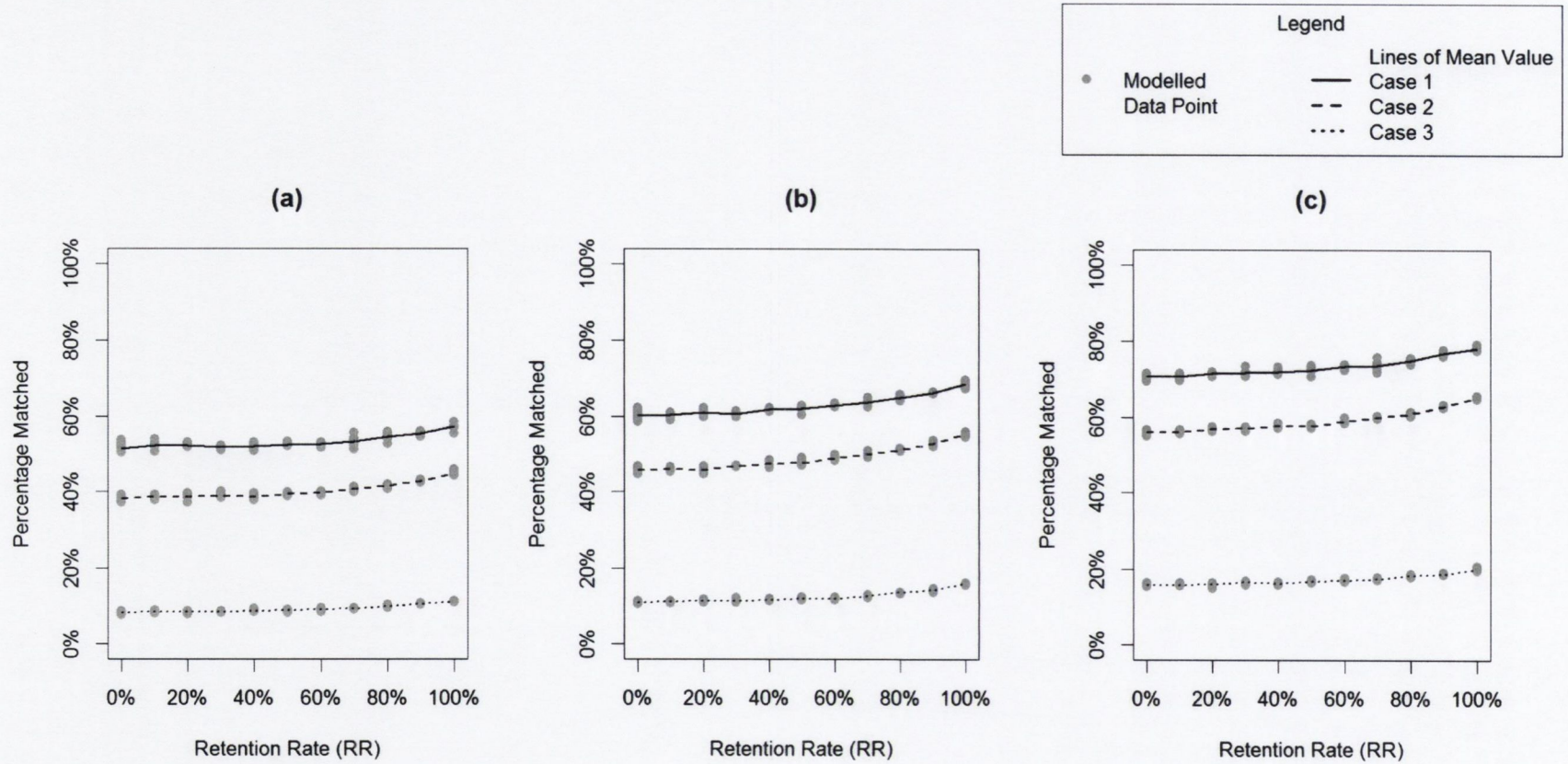

Figure 6.34: Variation in Retention Rate with 10 Batches and 1/3rd Initial Drivers for (a) Case A, (b) Case B and (c) Case C

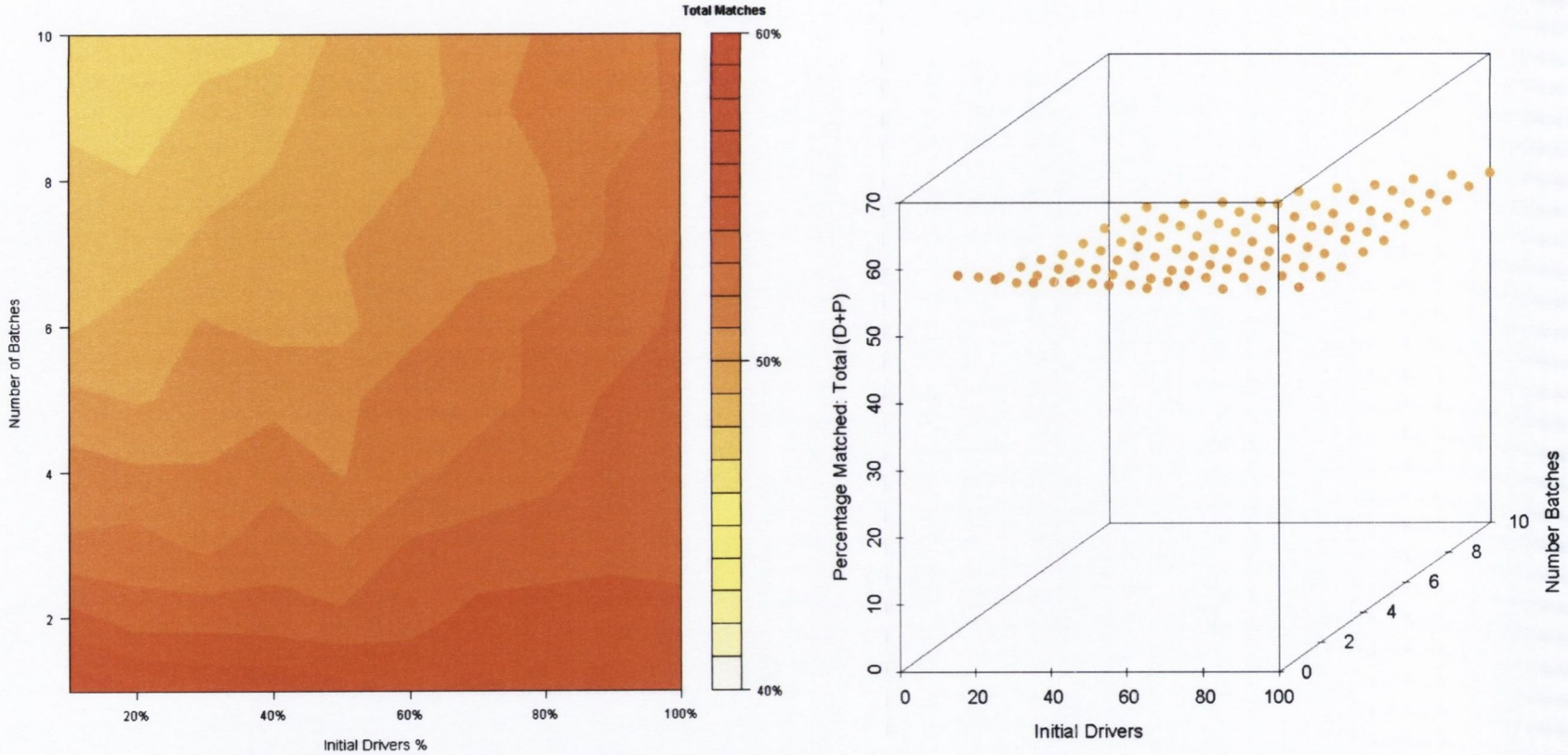

Figure 6.35: Case 2 B – Contour Plot showing relationship between Number of Batches and Proportion of Initial Drivers at Retention Rate=50%.

6.8.3 Retention Rate

The effect of lowering the Retention Rate (RR) for unmatched passengers is related to both the number of batches (B) and the proportion of drivers who register as ID_j. Figure 6.32 and Figure 6.33 therefore present the results of analyses of 5 and 10 batches respectively. In both these Figures, no registrants join in the category B_j.

In Case A (Figure 6.32 (a), Figure 6.33 (a)) where there are also no P_f, all potential drivers are available to all passengers and the retention rate therefore has no impact. In Case B (Figure 6.32 (b), Figure 6.33 (b)) and Case C (Figure 6.32 (c), Figure 6.33 (c)) lower Retention Rates result in fewer matches and by comparing Figure 6.32 and Figure 6.33, we can also see that there is a small reduction in the match rate as the number of batches increases.

Figure 6.34 demonstrates that when the proportion of Initial Drivers (ID_j) is decreased, the effect of a reduced Retention rate is exacerbated for Case A (compare Figure 6.33 (a) to Figure 6.34 (a)) and Case B (compare Figure 6.33 (b) to Figure 6.34 (b)). This is as a result of more registrants seeking an exclusively driver (B_j) role within the batches. Early batches therefore have few available drivers and when the retention rate is low, early passengers do not participate in later matching and consequently fail to identify a match.

Figure 6.35 is analogous to Figure 6.31, except that the RR has been increased to 50%. The contour lines follow the same patterns as Figure 6.31, however with the increase in RR the match rates achieved are higher in the extreme cases, i.e. in the 10 batch, 10% Initial Driver region.

6.9 Discussion

This chapter has analysed four models of ride sharing, each of which built on the previous model. The next section summarises the results of each model in turn, as found in the previous 4 sections. These results and match rates are then compared with the results achieved by models designed in previous research. A final section draws conclusions based on the overall model results.

6.9.1 Summary Results

In this section the results of each of the four models are summarised and the key findings for each model are highlighted.

The analysis of the BCMA model illustrates that if a ride-matching service is to operate effectively and identify matches for a high proportion of registrants, than two factors are important. These are the willingness of individuals to ride share when matches are geographically less convenient and the number of people registering with the service. The two other factors examined, i.e. flexibility in arrival times at the work place and a willingness to share with more than one additional passenger, are found to be far less important in increasing the number of matches made.

In the analysis of the second model, the FMA the key finding of these analyses is made. That is that registrants who are willing to act as either a driver or passenger can greatly increase match rates. It is also found that where drivers offer passengers more than one seat, increases in the match rate can be achieved by reducing the number of drivers. Optimal matching is achieved when most registrants are willing to undertake the role of driver or passenger and when once assigned the role of driver, registrants are willing to carry 3 passengers.

In the analysis of the third model, the SMA, the potential impact of individual preferences on the match rate is examined. This algorithm is somewhat hampered by a lack of research in the area. The literature review (described in Chapter 2) identified no papers which describe the characteristics of ride share pairs. It is therefore unclear how much of an influence personal preferences may have on an individual's decision to accept a match. The analysis presented suggests that as personal preference become more specific, a reduction in the match rate occurs and that this reduction in match rate is not linked to other registrant behaviours such as flexibility or numbers participating.

In the analysis of the fourth model, the DMA, the model moves from a static model to a dynamic model. This model more closely represents modern ride-sharing as supported by smart phone applications and instant matching. These new technologies offer the promise of greater flexibility in ride sharing for individual registrants, and thus of greater participation. However the analysis finds that when matching occurs in smaller groups and when registrants provide details of their journeys at separate times (i.e. in batches), the match rate is negatively affected. This negative impact is somewhat mitigated if drivers are encouraged to register early and wait to receive matches, registrants are flexible to act as either a driver or a passenger and if passengers are willing to be included in multiple batches. Care should also be taken since the added convenience of a dynamic matching service may also encourage registrant participation above that of a static matching service. If that is the case, the higher daily registration of a dynamic RSS may produce a higher match rate than a less popular static RSS.

In summary, the analysis finds that when establishing a RSS the key is to encourage individual registrants to adopt flexible roles, be willing to travel additional distances to achieve a match, to register for the service before a specific time and to be willing to accept a match at the latest point possible. Early registration for drivers is particularly important.

6.9.2 Results in Context of Previous Research

The models discussed in this chapter are best considered in the context of Agatz et al. (2011) and Tsao and Lin (1999). Both these papers evaluate the potential of ride sharing, with Tsao and Lin (1999) taking a mathematical approach based on a uniform distribution of homes and work places while Agatz et al. (2011) base their study on simulated data from the Metro Atlanta region. Each of the four models is now discussed in turn and subsequently the results are compared to those of Tsao and Lin (1999) and Agatz et al. (2011)

Agatz et al.'s (2011) model which is modelled on a real population in the metro area of Atlanta finds results more similar to those found under this analysis with models typically achieving 60% - 80% matches. Atatz et al.'s (2011) work is based on a population of 1.48 million commuters; living in an area of 6,500 square miles (16,835km^2) and within the model, each individual resides and works at the centre of one of 2024 travel analysis zones. On average each zone is therefore 8.3km^2. Matches are considered feasible if, subject to time constraints, the total ride share trip (including detours) is shorter than the sum of the separate driver and passenger trips. Agatz et al. (2011) argue that this arrangement will result in an overall cost saving and thus be acceptable to registrants.

Due to the differing algorithms used, the different population densities, the placement of origin and destinations at population centroids by Agatz et al. (2011) and the different pattern of commute trips the results obtained by Agatz et al. (2011) and in this work are not directly comparable. In particular the models presented here differ from Agatz et al.'s (2011) in that they consider a maximum possible detour instead of a detour proportional to the trip length.

However, some general comparisons are possible. The mean trip length in the POWSCAR sample is 7.35km with a median trip length of 6km. Case 1 with a permissible detour $Dist_T$=5km should therefore be somewhat similar to the conditions considered by Agatz et al. (2011). Under a 2% participation scenario, Agatz et al. (2011) successfully identifies matches for 28.7% of registrants under a first come first served scenario and for 67.0% of registrants using commercial optimisation software. The matching algorithm developed for this thesis successfully identifies

matches for 58.2% of registrants under the most similar scenario Case 1-A. Overall this suggests that a satisfactory optimisation of the matching process has been achieved.

The results presented by Agatz et al. (2011) and in this thesis differ from those of Tsao and Lin (1999). Tsao and Lin (1999) find that with a uniform distribution of population, the likelihood of finding feasible ride match pairs is low, and thus large scale ride sharing services are very unlikely to succeed. Tsao and Lin assumed that 660 individuals lived and worked in each square mile area (2.6km^2), that each individual was willing to ride share with any individual who shared the same 2*2 mile grid squares (10.4km^2) as home and work locations. Our population of 205,028 driver commuters in the Dublin County area, has a slightly lower average population density of 576/sqmile (223/km^2).

In real cities, Tsao and Lin's (1999) assumptions break down because homes and workplaces are not evenly distributed. For instance, in the model produced for this analysis, a four square mile (10.4km^2) area (equivalent to Tsao and Lin's grid square) in Dublin's city centre, records 32,700 employees working in the area. Using one of Tsao and Lin's most optimistic model, with 660 jobs/sq mile and an average commute distance of 10 miles, and applying a rate of 5% population participation, Tsao & Lin's results suggest an average match rate of below 2%. The most similar model produced in this analysis, the 2-A model described in Table 6.3, suggests a match rate of 45.6% for Dublin, higher if one removes the time constraint.

The analysis therefore finds that Tsao and Lin's (1999) mathematical model of origin-destination based ride sharing reaches an incorrect conclusion. In real situations, those who work in certain areas tend to live in a similar set of areas. Furthermore while average residential and work place densities may be low, specific areas have higher densities. As a result of these two factors viable commuter match pairs can be identified.

6.10 Conclusion

The results of these models suggest key areas of focus for practitioners seeking to establish a successful ride sharing service. These are

1) Flexible Roles: Allowing and incentivising registrants to register in a flexible role,
2) Geographic Inconvenience: Incentivising registrants to travel greater distances to achieve a match,
3) Timely Registration: Incentivising registrants, particularly drivers, to register in advance of a specific deadline,

4) Critical Mass: Achieving a sufficient number of registrants to allow each registrant a good probability of achieving a match within an appropriate distance.

7 GEOGRAPHIC, ENVIRONMENTAL AND ECONOMIC IMPACTS OF RIDE SHARING

7.1 Introduction

Using the understanding of ride sharing gained from the analysis in Chapter 6, the background provided in Chapter 1, and the literature review in Chapter 2, this Chapter estimates the environmental and economic impacts if a ride sharing service were to operate in a geographic area. The Dublin County area is again used as a case study here.

The first part of this chapter develops the methodology with which these analyses are carried out. That is it describes the models which are analyzed and derives the figures used to calculate the environmental and economic impacts. Two models are analyzed in this chapter: the Original Model and the Goodwill Model. The analysis of these models is then followed by a case study of a targeted rollout of the RSS to those working in a selected area, in this case Dun Laoghaire Town Centre.

The Original Model uses the understanding gained from Chapter 6 to select reasonable sets of constraints. Then using the model algorithms described in section 6.3.3 (Static FMA) and Section 6.3.5 (Dynamic DMA) the RSS is modelled over multiple days. From the results of these runs the environmental and economic impacts of the RSS are calculated and an understanding of the characteristics of individuals who successfully find matches is gained. For comparative purposes a summary of the results for key models from Chapter 6 is also presented.

The Goodwill Models then introduce an element of user feedback to the system by preferentially selecting those who successfully find matches. In the Original Models each commuter is equally likely to register for the service, regardless of their previous success or failure in finding a match. In the Goodwill Models all users are first awarded a baseline points value. Registrants who successfully find matches are then awarded additional points while registrants who do not find matches are docked points. Subsequent days in the models then select registrants from those whose points are above a threshold value. If the number of commuters above the threshold value is too small, the model randomly selects the balance of registrants from those with a score below the threshold value. This preferential selection technique is similar to that used by Agatz et al. (2011)

To analyse the Goodwill Models, the models run for the Original Models are run again over multiple days to allow the Goodwill scoring system to take effect. The changes to the match rates which occur as the participating pool of ride sharers becomes limited to those who are likely to identify a match are then examined. The results of these runs are used to calculate the environmental and economic impacts of the RSS operating under these conditions. An understanding of the characteristics of the individuals who remain within the participating pool is also gained.

The case study of Dun Laoghaire Town Centre (DLTC) then examines the impact of the Original Models and the Goodwill Models if registration with the RSS is restricted to those meeting certain criteria, in this case reporting a workplace in DLTC. The smaller number of potential registrants allows a more comprehensive evaluation of the impacts of different registrant behaviours to be undertaken.

The remaining part of this chapter is structured as follows. In Section 6.2 we describe the methodologies used in this set of analyses. First the three sets of models presented in this chapter are described in more detail. Subsequently we describe the methodology used to calculate the economic and environmental impacts of the operation of the RSS. In Section 6.3 and Section 6.4, we present the results of the Original Models and the Goodwill Models respectively. These results are presented using a similar structure to that used in Chapter 5, i.e. an economic & environmental, and a geographic analysis are presented separately. In Section 6.5 we present the results of the DLTC case study. Finally, in section 6.6 we conclude with a brief section discussing the main findings of this chapter.

7.2 Methodology

This section briefly describes the models and methodologies used to analyse the environmental and economic impacts of the RSS.

7.2.1 Original Models

When we consider the range of commuter journey distances presented in Figure 6.11, it's clear that of the constraints used in Chapter 6, only Case 3 is viable for an origin-destination based RSS. These constraints are:

- $Dist_H < 0.75km$

- $Dist_W < 0.75km$
- $Dist_T < 1.25km$
- $t < 15$ minutes
- 3 Seats are available with each Driver

These constraints represent a distance which is generally walkable, and which does not represent an excessive delay to the average journey of 7.35km. These constraints are adopted as the foundation of the analysis in this chapter. In conjunction with these constraints three levels of population participation: 2%, 5% and 10%; are used.

Based on the results of Chapter 6, a static FMA model (based on the Flexible Matching Algorithm, Section 6.3.3) and a dynamic DMA model (based on the Dynamic Matching Algorithm, Section 6.3.5) are selected. For the static FMA model we select a P_f/P of 0.5 and a D/P of 0.5, this is Case B as described in Section 6.7 and Table 6.4. For the dynamic DMA model a P_f/P of 0.5 and a D/P of 0.5, is selected. To this model we add a 5 batched model where $1/3^{rd}$ of the drivers register before the start of matching and 20% of unmatched passengers are retained at the end of each batch. That is: NB=5, ID=1/3 D, and RR=0.2. For clarity, a summary of the numbers registering in each category for each variation of the model is presented in Table 7.1 below.

Table 7.1: Numbers Registering in Each Category for the Models Used

	Static (FMA)			Dynamic (DMA)		
	2%	**5%**	**10%**	**2%**	**5%**	**10%**
Total Registrants	4101	10251	20503	4101	10251	20503
Drivers (D)	1367	3417	6834	1366	3419	6833
ID_j	*1367*	*3417*	*6834*	*456*	*1139*	*2278*
Total B_j	*0*	*0*	*0*	*910*	*2280*	*4555*
Passengers (P)	2734	6834	13669	2735	6830	13670
Total B_i	*1367*	*3417*	*6835*	*1365*	*3415*	*6835*
Total B_f	*1367*	*3417*	*6834*	*1370*	*3415*	*6835*
Total Per Batch				729	1822	3645
B_j	-	-	-	*182*	*456*	*911*
B_i	-	-	-	*273*	*683*	*1367*
B_f	-	-	-	*274*	*683*	*1367*

7.2.2 Goodwill Models

In the Original Models described in Section 7.2.1, all commuters are equally likely to participate in the RSS, however in reality, this is unlikely. Those who participate successfully are likely to continue to participate, while those who participate unsuccessfully will not.

Using the same models as those described in Section 7.2.1, we therefore add a "goodwill" element to each individual's likelihood of participation. This operates as follows:

1. Each individual is assigned a starting Goodwill Score of 1.
2. In accordance with the appropriate algorithm in Chapter 6, the model is run for one day and the Goodwill Scores are augmented as follows:
    a. If an individual does not register, their Goodwill Score remains unchanged
    b. If an individual registers and successfully achieves a match (as driver or passenger), their Goodwill Score is increased by 0.5
    c. If an individual registers and does not achieve a match, their Goodwill Score is decreased by 0.5.
3. The model is then re-run in accordance with the appropriate algorithm described in Chapter 6; however registrants are randomly selected from the pool of individuals with a Goodwill Score greater than zero. If insufficient individuals with a Goodwill Score greater than zero remain, all registrants with a Goodwill Score greater than zero are selected and the balance of registrants is made up from those with a Goodwill Score less than or equal to zero.

Each individual will therefore register at least twice over the course of the model. If they do not successfully identify a match in these two registrations, it is unlikely that they will register at a later point.

7.2.3 Targeted Rollout Models: Dun Laoghaire Town Centre

The Targeted Rollout Models are a case study based on the previous two models, i.e. the Original Models and the Goodwill Models. The Targeted Rollout Models envisage a limited rollout of the RSS, whereby registrants are restricted to those meeting certain criteria.

The case study is chosen to mimic a real situation where a governmental body promotes ride sharing to commuters who work in a specific area as means to achieve goals such as an improved environmental profile or the relief of parking congestion. In such situations the use of a ride sharing service can be reinforced through targeted publicity and incentives such as designated

parking spaces, reduced parking rates, a guaranteed ride home scheme etc. Higher levels of population participation should therefore be more readily achievable.

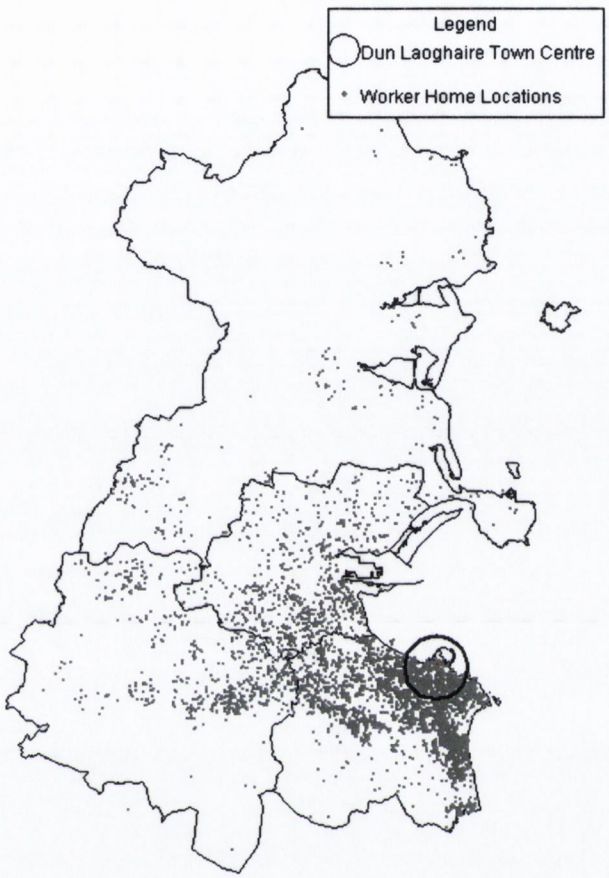

Figure 7.1: Home Locations of those Driving to DLTC

The area selected is Dun Laoghaire Town Centre (DLTC). During the analysis of the Goodwill Models (see Figure 7.11) DLTC emerged as a location where a high percentage of the workforce could successfully participate in the RSS. DLTC is a local centre for shopping, business and leisure facilities. As the administrative centre of the Dun Laoghaire-Rathdown administrative county, it is also a centre for local government. For these reasons it was chosen as the case study area.

Under the Targeted Rollout Models, only those who work within a 2km radius of DLTC are eligible to register with the RSS. 4980 individuals are therefore eligible to register with the RSS. The extent of this area and the home locations of those who work within it and drive to work are illustrated in Figure 7.1.

As a consequence of the smaller number of potential registrants, model simulations can be run rapidly. This allows for a more in depth analysis and a greater number of model variations than with previous models. In the analysis of the Goodwill and Original Models of Dublin County and the initial exploratory models of DLTC, it was observed that the percentage of the registrant population remaining in the active population after stabilization appears to be related to the match rate calculated under the Original Models. An exploratory analysis of the Original Models as they would operate in DLTC was therefore carried out, and based on the results of this analysis selected Goodwill Models were further analysed. The scenarios chosen and the results of these analyses are described in section 7.5.

7.2.4 Environmental Analysis

The environmental analysis is carried out using a methodology similar to that described in Chapter 4 and Chapter 5, i.e. a distance foregone is first calculated and an average rate of CO_2 savings per unit distance is applied in order to estimate a total CO_2 reduction. The full procedure is described in more detail below.

To calculate the distance travelled, several simplifications are made. Using the home location and work location of each commuter (generated in Section 6.3.1), an "as the crow flies" distance for each commuter's journey was calculated. This is a conservative estimate as the actual distance travelled by each individual will be longer due to street layouts etc. We assume that driving this distance in a vehicle occupied only by the driver is foregone by any individual successfully matched as a *passenger* who uses the RSS. We ignore any additional distance which a driver may incur if they deviate from the normal route to collect passengers. This approach is similar to that used by Caulfield (2009) and Agatz et al. (2011).

From the analysis of the Irish car fleet carried out in Section 4.2 and Section 4.3, an average CO_2 emissions/km value for cars on the road at the time of the survey was calculated. This figure was 149.0g/CO_2/km. Based on responses to the survey, an average emissions value was also calculated for the cars which respondent's working in Dublin reported owning. This value was 147.3g/CO_2/km. The CMT emissions calculator (Environmental Protection Agency Ireland, 2009) was also provided an average value of 150g/CO_2 per km, which was used as an estimated emissions rating for cars owned by the CSS. As each of these values is close, 150g/CO_2/km is adopted as the rate of CO_2 savings.

It is assumed that the service operates on each working day. As Ireland has 9 bank holidays, the calculated environmental impact for each day is multiplied by 251 days to give an annual figure. It should also be noted that the calculated impacts are only applicable to the morning commute. Any RSS would also operate during the evening commute which would approximately double the calculated impacts.

7.2.5 Economic Analyses

The approach when conducting the economic analysis is similar to that used for the environmental analysis, i.e. the distance saved by each matched passenger is converted to a financial saving by calculating costs and savings per km. We therefore estimate two figures - the cost saved by the passenger by not travelling in their own vehicle, and the fee paid by the passenger to travel with the driver when ride sharing. The net cost saving is the difference between these two figures. The cost saved by the passenger not travelling in their own vehicle is further broken down and both an operational cost and a total cost are calculated. The basis on which cost and spending estimates are made and the methods used to calculate a final result are described in more detailed below.

As with the environmental analysis, it is assumed that the service operates on each working day, therefore the calculated economic impacts for each day are multiplied by 251 days to give an annual figure. It should again be noted that the calculated impacts are only applicable to the morning commute. Any RSS would also operate during the evening commute which would approximately double the calculated impacts.

Passenger Spending on RSS & RSS Charges

We expect that the passenger will pay the driver for the ride online via the smart phone app or website used to arrange the ride share. This fee is then distributed proportionally to the driver and the ride sharing company. No ride sharing company is successfully operating in Ireland at this time, and those that operate on a small scale price the service in US$ and do not provide a breakdown of how fees are calculated. Using the Car.ma app some illustrative prices for short journeys in Dublin at rush hour include $1.50 for 5.6km, $2.50 for 9.7km and $2.25 for 12.1km. ("Carma - Get there together", 2014)

The RSS would also operate somewhat in competition with Dublin's bus services, which has an obscure and complex pricing system. Bus fares in Dublin are calculated based on the number of

stops travelled rather than distance, however if a leap card[5] is used, a journey of up to 2km is likely to cost €1.45, 2-4km is likely to cost €1.95, 4-7km is likely to cost €2.15 and €2.50 thereafter (Dublin Bus, 2012). Taxis in Dublin operate by charging a flat fee for the first km (€4.10) and an additional fee for each km thereafter (€1.03 for each of the next 14km) (National Transport Authority, 2008). It seems likely that a RSS would offer a similar pricing structure, though at rates closer to those of the bus service.

It is therefore estimated a charge to the passenger of

- 75c for the first km and
- 10c for each additional km.

It is also estimated that the driver receives 80% of this amount while the RSS takes 20% to cover operating costs and profit.

Gross Passenger Savings: Cost Savings per Km for Passengers

Three sources of information are available regarding the costs of travel in Dublin. These are the survey undertaken as part of this research (described in Chapter 3 & 4), statistics published by the Central Statistics Office, and guidance on the cost of travelling in motor vehicles published by the automobile association of Ireland.

The 816 survey participants used as a sample in Chapter 5 are used here to estimate a cost per km of travel for the working population of Dublin. The 816 participants reported travelling a total of 179,414km/fortnight in private cars (4.66million km/annum). The calculated ownership and depreciation costs of these individuals were €719,208pa; the reported insurance, maintenance and motor costs were €645,303pa; and their reported spending on operational expenses (e.g. fuel) was €818,873pa. This suggests a total cost per km driven of 46.8c and an operational cost per km driven of 17.6c.

Several sets of statistics provided by the Central Statistics Office may also be combined to estimate the cost of travel in motor vehicles for Dublin residents. Per the descriptions given in Section 3.3, the 466,461 households of Dublin, own an estimated 541,966 cars and each household spends €88.44 per week (€4598.88pa) on expenses related to car ownership and travel. Using the breakdown of spending provided by the Household Budget Survey 2009 – 2010

[5] The Leap Card is a reusable plastic smart card integrated ticket used in Dublin. It is similar to the Oyster Card in London.

(CSO, 2012e), we find that of this figure, on average each Dublin household spends €1600.56pa on operational costs.

However the household budget survey does not provide us with an estimate of the distance travelled in each of these cars. As discussed in section 3.3, the National Travel Survey (CSO, 2011b) provides outline details of the travel patterns of Dublin residents. Dublin residents are found to travel an average of 151km, making 54% of journeys as the driver of a car. This would suggest that the 1,273,068 residents of Dublin each add an average of 4240km/year to the mileage of one of the 541,966 cars owned in the city. Combining this figure with the figure from those of that Household Budget Survey 2009 – 2010 (CSO, 2012e), produces an estimated total cost per km driven of 39.7c per km and an operational cost per km driven of 13.8c.

Finally the automobile association of Ireland produces statistics regarding the typical cost of motoring in Ireland. In 2011, based on a typical car, in this case a Band C car, travelling 16,000km per year, the AA estimated an estimated total cost per km driven of 73.86c, of which 23.04c is an operational cost per km (Automobile Association, 2010).

As these figures have considerable variation, to estimate the cost saving per km driven, we average these three sources of information. We therefore estimate:

- Total cost per km driven: 53.5c
- Of which, operational cost per km driven: 18.1c

Where the operational costs includes only the direct cost of driving a specific distance (e.g. wear and tear, fuel) and the total costs includes all costs associated with car ownership (e.g. ownership costs, depreciation costs, tax).

Net Passenger Savings: Cost Savings per Km for Passengers

The net savings of passengers are obtained by calculating the difference between the passengers' spending when using the RSS and the passengers' saving by not using their own car. Both a total savings and an operational savings figure are calculated.

The actual savings realised by individual ride sharers will depend on personal circumstances. If the RSS enables the sale of a car, the total cost will be realised. If the RSS does not enable the sale of a car or any additional behaviour change, only the operational cost will be realised. Many intermediate circumstances are also possible, such as the sale of a household second car creating

additional demands on the primary vehicle, or the sale of a car necessitating additional spending on other forms of transport. It is therefore expected that for most registrants, the actual savings realised will fall between the operational cost and the total cost. The total cost and the operational cost therefore represent upper and lower bounds for savings.

As the structure of pricing for the RSS differs from that of travel in a registrant's private car, the registrant will only make savings if the journey is of sufficient length. A breakeven distance for each savings type is therefore calculated:

- Breakeven for Total Cost: 1.49km
- Breakeven for Operational Cost: 8.02km

7.3 Original Models Results

To carry out this phase of the analysis, each of the 2% models was run at 10,000 times, each of the 5% models was run 2005 times, and each of the 10% models was run 1005 times. Thus each individual commuter participated in ride sharing at least 57 times in each model. Using the results of these model runs, the economic and environmental impact of each version of the model can be calculated and the likelihood of each individual commuter achieving a match estimated.

7.3.1 Economic and Environmental Analysis

Using the figures given in Section 7.2, the impacts of an RSS in Dublin, when participants register and accept matches in accordance with the figures presented in Table 7.1 are estimated. Detailed results are presented in Table 7.2. These results are based on the morning commute only, and it is expected that impacts calculated can be approximately doubled if the evening commute were also to be included. With the exception of drivers with 2 passengers and drivers with 3 passengers, the 95% confidence interval for all results in Table 7.2, is less than ± 0.5%.

Table 7.2: Detailed Economic and Environmental Results: Basic Static and Dynamic Models on Morning Commute Journeys in County Dublin

	Static (FMA)			Dynamic (DMA)		
	2%	5%	10%	2%	5%	10%
Registrants Per Day	4101	10251	20503	4101	10251	20503
Daily Participation Characteristics						
Drivers						
Unmatched	1278.9	2961.0	5366.5	1305.8	3098.0	5768.0
Matched	88.1	456.0	1467.5	60.2	321.0	1065.0
Drivers w/1 Passenger	*83.8*	*412.2*	*1254.5*	*57.5*	*291.1*	*909.3*
Drivers w/2 Passengers	*4.0*	*39.4*	*181.7*	*2.6*	*26.5*	*129.5*
Drivers w/3 Passengers	*0.2*	*4.4*	*31.2*	*0.2*	*3.3*	*26.2*
Passengers						
Unmatched	2641.4	6329.7	11957.4	2662.6	6428.5	12272.2
Matched	92.6	504.3	1711.6	72.4	401.5	1397.8
Match Rate (Total)	4.4%	9.4%	15.5%	3.2%	7.0%	12.0%
Individual Characteristics						
Distance Travelled by:						
Average Registrant (km)	*7.4*	*7.4*	*7.4*	*7.4*	*7.4*	*7.4*
Matched Passenger (km)	*5.1*	*5.2*	*5.3*	*5.0*	*5.1*	*5.2*
Average Passenger Trip Cost	€1.16	€1.17	€1.18	€1.15	€1.16	€1.17
Average Driver Trip Income	€0.97	€1.03	€1.10	€1.11	€1.16	€1.23
Environmental Impacts (Total Per Annum)						
1000 kg CO_2 Saved	17.6	98.3	342.8	13.7	77.4	275.6
Economic Impacts (Total Per Annum)						
Total Passenger Spending on RSS	€26,852	€147,777	€507,775	€20,928	€117,080	€411,797
Gross Passenger Savings						
Total	*€62,843*	*€350,429*	*€1,222,644*	*€48,783*	*€275,901*	*€983,042*
Operational	*€21,261*	*€118,556*	*€413,642*	*€16,504*	*€93,342*	*€332,581*
Net Passenger Savings						
Total	€35,991	€202,652	€714,869	€27,855	€158,821	€571,245
Operational	-€5,591	-€29,221	-€94,133	-€4,424	-€23,738	-€79,216
RSS income	€5,370	€29,555	€101,555	€4,186	€23,416	€82,359

From Table 7.2 a number of important findings may be noted. First, as expected from Chapter 6, the match rate is low, totalling between 3.2% and 15.5% of registering users. On average, those who successfully identify matches have shorter commute journeys than the registrant population. Together these two results mean that if the RSS operates in accordance with this model, the RSS will have a relatively low impact on CO_2 emissions and on commuter travel costs. This remains true even when a doubling of the results for the evening commute journey is allowed for. At

participation levels below 10%, it is also unlikely that an RSS will be able to sustain itself at the forecast income levels.

Table 7.3 then presents an overview of the results obtained for a selection of the models developed in Chapter 6. The labelling of the results in Table 7.3 is in accordance with the Cases (1, 2, 3 & A, B, C) described in Section 6.6 and Section 6.7.

Under Case 1 and Case 2, registrants are willing to take much longer detours ($Dist_T$=5km and 3km respectively) in order to reach suitable pick up and drop off points. In spite of the lower levels of population participation (2% and 5% respectively), this behaviour leads to higher match rates than those presented in Table 6.3 and consequently higher CO_2 savings and RSS income levels.

The results in Table 7.3 also show that as the Cases move from A to B to C (i.e. the flexibility of registrants' increases), the match rate and the average distance travelled by a matched passenger also increases. Consequently the environmental and economic impacts of the model increase.

With a few exceptions, the dynamic models presented produce RSS income and CO_2 savings, slightly below those of their equivalent static models. Exceptions occur when the conditions of the dynamic model are very close to those of the static model, e.g. RR = 1 and ID = 1.

While models based on Case 1 have the highest match rates, and Case 3 have the highest participation levels, the balance of participation and match rates in Case 2 produces the highest economic and environmental performance of the three models under consideration. Overall Model 2C is the best performer, achieving the highest CO_2 savings and income for the RSS.

Table 7.3: Summary Economic and Environmental Results: Selection of Chapter 5 Models on Morning Commute Journeys in County Dublin

Case & Type	ID	NB	RR	Match Rate	Number Matched Passengers	Avg. Pass. Distance	1000kg CO_2	Savings		RSS Income
								Total	Operational	
1-A-Static	-	-	-	58%	1442.1	5.98	324.95	€707,079	-€59,811	€90,384
1-B-Static	-	-	-	68%	1707.1	6.14	394.76	€866,289	-€65,349	€108,339
1-C-Static	-	-	-	79%	2045.9	6.28	483.45	€1,068,205	-€72,730	€131,218
2-A-Static	-	-	-	45%	2749.0	5.69	589.18	€1,260,119	-€130,338	€168,256
2-B-Static	-	-	-	55%	3391.9	5.83	745.05	€1,607,262	-€151,065	€210,019
2-C-Static	-	-	-	67%	4176.5	5.95	935.95	€2,032,861	-€175,989	€261,074
3-A-Static	-	-	-	11%	1215.7	5.25	240.36	€498,691	-€68,554	€71,717
3-B-Static	-	-	-	16%	1712.2	5.32	342.88	€715,012	-€94,192	€101,587
3-C-Static	-	-	-	20%	2310.4	5.30	461.05	€960,108	-€127,979	€136,863
1-A-Dynamic	1/3	5	0	52%	1315.4	5.79	286.95	€617,530	-€59,664	€81,182
1-A-Dynamic	1/3	5	1/5	53%	1323.2	5.88	292.76	€633,117	-€57,794	€82,211
1-A-Dynamic	1/3	5	1	57%	1437.7	5.93	321.05	€696,479	-€61,190	€89,717
1-A-Dynamic	1	5	0	58%	1430.5	5.96	320.87	€697,143	-€60,120	€89,461
1-A-Dynamic	1	5	1/5	58%	1435.0	5.95	321.4	€697,926	-€60,567	€89,677
1-A-Dynamic	1	5	1	58%	1436.1	5.96	322.03	€699,590	-€60,401	€89,797
1-A-Dynamic	1/3	10	0	52%	1294.5	5.82	283.46	€610,851	-€58,123	€80,034
1-A-Dynamic	1/3	10	1/5	52%	1316.0	5.74	284.28	€609,704	-€61,195	€80,845
1-A-Dynamic	1/3	10	1	57%	1434.7	5.94	320.65	€695,816	-€60,915	€89,566
1-A-Dynamic	1	10	0	58%	1438.6	5.95	322.42	€700,305	-€60,600	€89,930
1-A-Dynamic	1	10	1/5	58%	1446.8	6.06	330.22	€721,593	-€57,731	€91,240
1-A-Dynamic	1	10	1	58%	1429.2	6.01	323.24	€704,220	-€58,620	€89,732
1-B-Dynamic	1/3	5	0	62%	1642.7	5.88	363.68	€786,673	-€71,623	€102,094
1-B-Dynamic	1/3	5	1/5	63%	1658.0	5.94	370.92	€805,151	-€70,209	€103,556
1-B-Dynamic	1/3	5	1	68%	1777.7	6.08	406.87	€889,907	-€70,315	€112,255
1-B-Dynamic	1	5	0	66%	1750.9	5.97	393.33	€855,001	-€73,259	€109,576
1-B-Dynamic	1	5	1/5	67%	1766.7	6.00	399.2	€869,459	-€72,662	€110,874
1-B-Dynamic	1	5	1	69%	1797.9	6.06	410.33	€896,616	-€71,754	€113,376
1-B-Dynamic	1/3	10	0	60%	1620.9	5.85	356.92	€770,638	-€71,704	€100,478
1-B-Dynamic	1/3	10	1/5	61%	1641.2	5.86	362.27	€782,821	-€72,132	€101,854
1-B-Dynamic	1/3	10	1	69%	1794.5	6.07	410.04	€896,332	-€71,353	€113,226
1-B-Dynamic	1	10	0	66%	1756.5	5.96	394.47	€857,397	-€73,558	€109,911
1-B-Dynamic	1	10	1/5	66%	1761.2	5.93	392.93	€852,149	-€75,155	€109,857
1-B-Dynamic	1	10	1	69%	1800.2	6.03	408.35	€890,531	-€73,186	€113,187
1-C-Dynamic	1/3	5	0	73%	2062.4	6.12	475.3	€1,041,888	-€79,817	€130,669
1-C-Dynamic	1/3	5	1/5	73%	2062.8	6.04	469.07	€1,023,750	-€83,246	€129,851
1-C-Dynamic	1/3	5	1	79%	2143.3	6.15	496.34	€1,089,714	-€81,659	€136,116
1-C-Dynamic	1	5	0	73%	2062.9	6.14	476.76	€1,046,039	-€79,114	€130,881
1-C-Dynamic	1	5	1/5	74%	2073.8	6.02	470.18	€1,025,176	-€84,449	€130,360
1-C-Dynamic	1	5	1	78%	2122.3	6.15	491.76	€1,079,852	-€80,707	€134,820
1-C-Dynamic	1/3	10	0	71%	2063.2	6.08	472.2	€1,032,779	-€81,624	€130,284
1-C-Dynamic	1/3	10	1/5	71%	2086.0	6.13	481.31	€1,055,456	-€80,426	€132,240

Table 7.3 Cont'd

Case & Type	ID	NB	RR	Match Rate	Number Matched Passengers	Avg. Pass. Distance	1000kg CO_2	Savings		RSS Income
								Total	Operational	
1-C-Dynamic	1/3	10	1	78%	2142.8	6.17	497.6	€1,093,440	-€80,899	€136,267
1-C-Dynamic	1	10	0	71%	2062.3	6.00	466.06	€1,015,103	-€84,798	€129,435
1-C-Dynamic	1	10	1/5	72%	2074.0	6.07	473.8	€1,035,648	-€82,521	€130,848
1-C-Dynamic	1	10	1	78%	2135.0	6.04	485.77	€1,060,417	-€86,008	€134,435
2-A-Dynamic	1/3	5	0	39%	2386.0	5.53	496.34	€1,050,129	-€121,244	€144,033
2-A-Dynamic	1/3	5	1/5	40%	2420.7	5.55	505.96	€1,072,343	-€121,715	€146,447
2-A-Dynamic	1/3	5	1	45%	2756.5	5.65	585.96	€1,249,563	-€133,304	€168,073
2-A-Dynamic	1	5	0	46%	2750.6	5.64	584.31	€1,245,735	-€133,234	€167,660
2-A-Dynamic	1	5	1/5	45%	2719.6	5.70	583.81	€1,249,350	-€128,439	€166,580
2-A-Dynamic	1	5	1	45%	2720.8	5.67	580.9	€1,240,697	-€130,220	€166,234
2-A-Dynamic	1/3	10	0	38%	2327.3	5.51	482.91	€1,020,733	-€118,927	€140,327
2-A-Dynamic	1/3	10	1/5	39%	2354.3	5.66	501.36	€1,069,829	-€113,376	€143,670
2-A-Dynamic	1/3	10	1	45%	2745.7	5.64	583.3	€1,243,601	-€132,976	€167,364
2-A-Dynamic	1	10	0	45%	2730.8	5.75	591.47	€1,269,755	-€126,125	€167,968
2-A-Dynamic	1	10	1/5	45%	2724.2	5.76	591.23	€1,270,118	-€125,184	€167,720
2-A-Dynamic	1	10	1	45%	2728.8	5.72	587.76	€1,259,294	-€127,819	€167,410
2-B-Dynamic	1/3	5	0	47%	3056.0	5.63	647.22	€1,378,349	-€149,088	€186,013
2-B-Dynamic	1/3	5	1/5	49%	3127.2	5.65	665.61	€1,420,068	-€150,776	€190,790
2-B-Dynamic	1/3	5	1	56%	3476.0	5.83	762.72	€1,644,789	-€155,239	€215,118
2-B-Dynamic	1	5	0	52%	3352.8	5.73	722.72	€1,548,876	-€156,742	€205,765
2-B-Dynamic	1	5	1/5	53%	3359.3	5.74	726.56	€1,558,951	-€155,721	€206,486
2-B-Dynamic	1	5	1	55%	3461.1	5.84	760.41	€1,640,518	-€154,051	€214,323
2-B-Dynamic	1/3	10	0	46%	3000.7	5.62	634.89	€1,351,616	-€146,729	€182,566
2-B-Dynamic	1/3	10	1/5	46%	2994.8	5.67	639.82	€1,366,866	-€143,105	€183,031
2-B-Dynamic	1/3	10	1	55%	3486.7	5.78	758.43	€1,630,588	-€159,299	€214,893
2-B-Dynamic	1	10	0	51%	3331.7	5.68	712.9	€1,523,838	-€158,597	€203,765
2-B-Dynamic	1	10	1/5	52%	3372.8	5.73	727.23	€1,558,699	-€157,564	€207,018
2-B-Dynamic	1	10	1	55%	3467.8	5.75	751.19	€1,612,689	-€160,124	€213,313
2-C-Dynamic	1/3	5	0	58%	4026.0	5.80	879.57	€1,893,908	-€181,869	€248,643
2-C-Dynamic	1/3	5	1/5	59%	4081.7	5.81	893.17	€1,924,280	-€183,610	€252,275
2-C-Dynamic	1/3	5	1	66%	4270.1	5.92	951.97	€2,064,032	-€182,607	€266,262
2-C-Dynamic	1	5	0	58%	4038.7	5.83	885.87	€1,910,105	-€180,549	€249,900
2-C-Dynamic	1	5	1/5	59%	4030.2	5.85	887.67	€1,916,722	-€178,180	€249,860
2-C-Dynamic	1	5	1	65%	4213.1	5.91	937.06	€2,030,120	-€181,350	€262,415
2-C-Dynamic	1/3	10	0	56%	4029.9	5.79	878.93	€1,891,419	-€182,850	€248,685
2-C-Dynamic	1/3	10	1/5	57%	4059.5	5.79	884.48	€1,902,672	-€184,690	€250,392
2-C-Dynamic	1/3	10	1	65%	4283.7	5.90	952.27	€2,062,711	-€184,653	€266,746
2-C-Dynamic	1	10	0	57%	4055.0	5.83	890.25	€1,920,148	-€180,839	€251,014
2-C-Dynamic	1	10	1/5	57%	4052.2	5.81	886.93	€1,910,985	-€182,169	€250,479
2-C-Dynamic	1	10	1	64%	4209.7	5.88	931.86	€2,015,590	-€183,602	€261,610
3-A-Dynamic	1/3	5	0	9%	931.0	5.18	181.53	€374,548	-€53,861	€54,581
3-A-Dynamic	1/3	5	1/5	9%	960.8	5.21	188.29	€389,284	-€55,075	€56,455
3-A-Dynamic	1/3	5	1	11%	1210.3	5.23	238.2	€493,322	-€68,836	€71,254

Table 7.3 Cont'd

Case & Type	ID	NB	RR	Match Rate	Number Matched Passengers	Avg. Pass. Distance	1000kg CO_2	Savings		RSS Income
								Total	Operational	
3-A-Dynamic	1	5	0	11%	1207.1	5.32	241.99	€504,850	-€66,256	€71,652
3-A-Dynamic	1	5	1/5	11%	1216.7	5.20	238.21	€492,305	-€69,867	€71,461
3-A-Dynamic	1	5	1	11%	1229.2	5.33	246.63	€514,689	-€67,358	€72,992
3-A-Dynamic	1/3	10	0	8%	886.3	5.16	172.08	€354,438	-€51,680	€51,866
3-A-Dynamic	1/3	10	1/5	8%	908.0	5.20	177.77	€367,382	-€52,146	€53,330
3-A-Dynamic	1/3	10	1	11%	1235.5	5.29	246.14	€512,231	-€68,657	€73,133
3-A-Dynamic	1	10	0	11%	1217.3	5.32	244.05	€509,144	-€66,820	€72,262
3-A-Dynamic	1	10	1/5	11%	1207.5	5.27	239.36	€497,149	-€67,748	€71,316
3-A-Dynamic	1	10	1	11%	1194.2	5.31	238.8	€497,678	-€65,879	€70,805
3-B-Dynamic	1/3	5	0	11%	1341.1	5.22	263.63	€545,725	-€76,442	€78,911
3-B-Dynamic	1/3	5	1/5	12%	1397.7	5.24	275.61	€571,236	-€79,210	€82,356
3-B-Dynamic	1/3	5	1	16%	1753.5	5.27	347.82	€722,584	-€98,263	€103,592
3-B-Dynamic	1	5	0	14%	1572.6	5.27	311.91	€647,970	-€88,140	€92,902
3-B-Dynamic	1	5	1/5	14%	1579.4	5.27	313.14	€650,426	-€88,590	€93,290
3-B-Dynamic	1	5	1	16%	1728.1	5.38	349.79	€732,467	-€93,048	€103,027
3-B-Dynamic	1/3	10	0	11%	1300.8	5.20	254.85	€526,841	-€74,608	€76,426
3-B-Dynamic	1/3	10	1/5	11%	1342.2	5.20	262.62	€542,613	-€77,162	€78,810
3-B-Dynamic	1/3	10	1	16%	1766.7	5.29	351.54	€731,231	-€98,401	€104,518
3-B-Dynamic	1	10	0	13%	1555.3	5.25	307.39	€637,687	-€87,749	€91,733
3-B-Dynamic	1	10	1/5	13%	1562.2	5.28	310.49	€645,565	-€87,201	€92,373
3-B-Dynamic	1	10	1	16%	1729.0	5.25	341.68	€708,782	-€97,580	€101,974
3-C-Dynamic	1/3	5	0	16%	2132.7	5.28	423.89	€881,338	-€119,044	€126,108
3-C-Dynamic	1/3	5	1/5	17%	2160.1	5.25	426.88	€885,544	-€121,904	€127,402
3-C-Dynamic	1/3	5	1	20%	2304.2	5.27	457.62	€951,153	-€128,821	€136,202
3-C-Dynamic	1	5	0	17%	2148.8	5.37	434.49	€909,444	-€115,957	€128,049
3-C-Dynamic	1	5	1/5	17%	2119.3	5.29	422.07	€878,238	-€117,851	€125,430
3-C-Dynamic	1	5	1	20%	2224.1	5.31	444.48	€926,124	-€122,845	€131,837
3-C-Dynamic	1/3	10	0	16%	2114.5	5.29	421.16	€876,395	-€117,552	€125,151
3-C-Dynamic	1/3	10	1/5	16%	2101.3	5.27	416.77	€865,787	-€117,779	€124,135
3-C-Dynamic	1/3	10	1	20%	2262.7	5.28	449.4	€934,115	-€126,476	€133,751
3-C-Dynamic	1	10	0	16%	2154.6	5.27	427.72	€888,865	-€120,552	€127,333
3-C-Dynamic	1	10	1/5	16%	2092.2	5.24	412.66	€855,391	-€118,498	€123,289
3-C-Dynamic	1	10	1	19%	2212.5	5.34	444.68	€928,600	-€120,843	€131,484

7.3.2 Geographic and Time Period Analysis

The difference between the average distance travelled by registrants and the average distance travelled by matched passengers confirms that the probability of an individual passenger achieving a match is not random, but instead depends on the features of their journey. Therefore this section analyzes the features of individual journeys which make it both more and less probable that an individual will successfully identify a match.

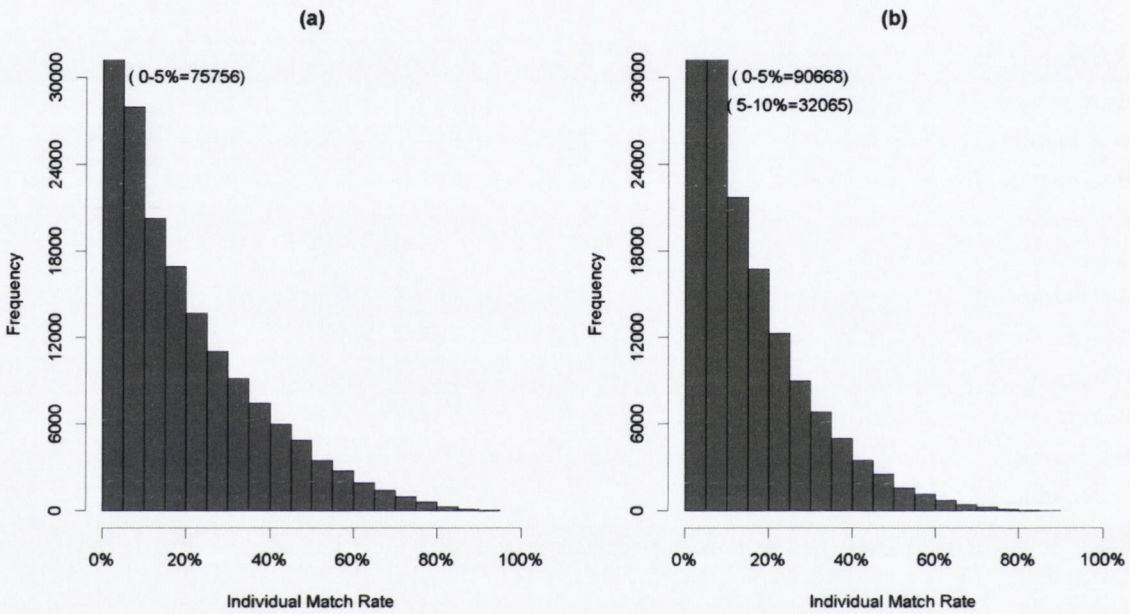

Figure 7.2: Proportion of Registrant Population in Each Individual Match Rate Band for (a) Static FMA and (b) Dynamic DMA models at 10% daily participation

Each potential registrant has an individual match rate, i.e. the percentage of times they successfully identify a match from all the times they register in order to seek a match. Figure 7.2 presents a frequency distribution of these individual match rates. It illustrates that under the original models the majority of potential registrants (N=205,028) have match rates below 10%, with very few individuals achieving match rates above 50%.

Figure 7.3 and Figure 7.4 present the geographic distribution of the average match rate. Match rates for models with 2% and 5% of the population are low, therefore only the results for the 10% models are presented. Figure 7.3 uses a yellow-red colour scale to present the mean match rate for registrants residing in each small area of Dublin. Figure 7.4 uses an identical colour scale to present the mean match rate for registrants working or studying in each small area of Dublin. These two figures illustrate that certain areas of the county have higher match rates than others.

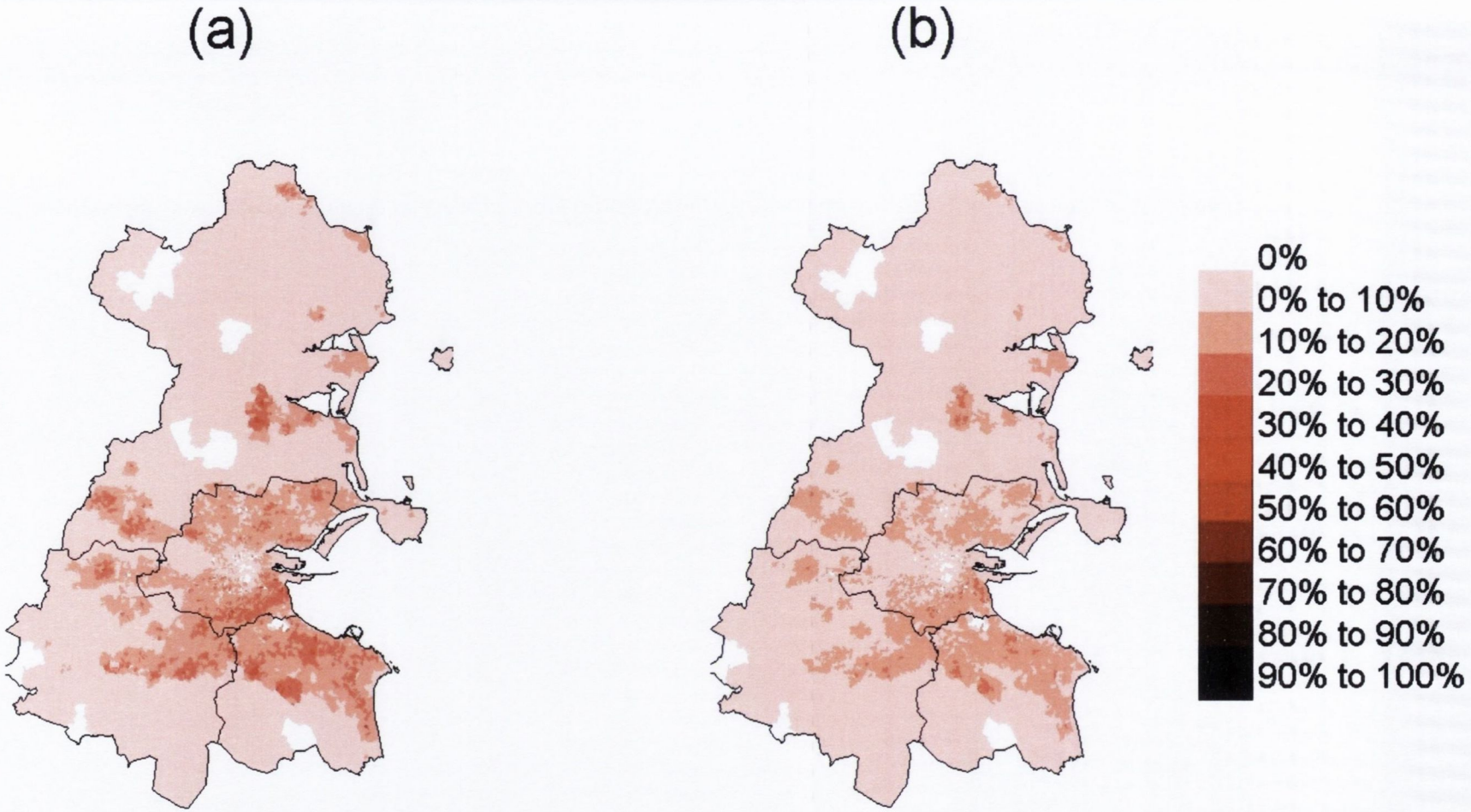

Figure 7.3: Original Models: Average Match Rate by Place of Residence for (a) Static (FMA) and (b) Dynamic (DMA) Models at 10% Population Participation

Figure 7.4: Original Models: Average Match Rate by Place of Work for (a) Static (FMA) and (b) Dynamic (DMA) Models at 10% Population Participation

When examining Figure 7.3, it is clear that in the central Dublin City Council area, those living outside the city centre have the highest chance of achieving a match, while in the remaining three areas, those living close to the Dublin City Council area and along the coast have higher chances of matches. When Figure 7.4 is examined in closer detail, it is clear that those working in the city centre and in the concentrated industrial estates along the M50 (e.g. City West, Sandyford, Blanchardstown, the Airport) have the highest match rates.

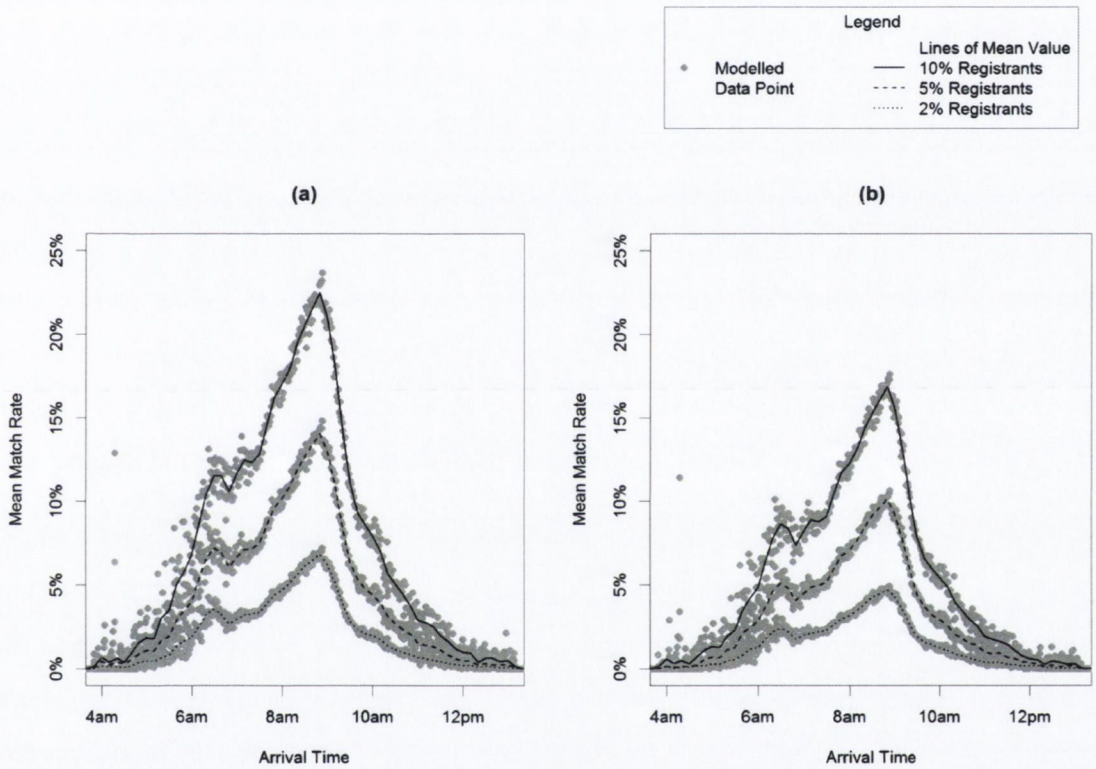

Figure 7.5: Original Models: Average Match Rate by Desired Arrival Time at Place of Work for (a) Static (FMA) and (b) Dynamic (DMA) Models.

Figure 7.5 presents the average match rate by desired arrival time. As expected it peaks around 9am and falls off sharply thereafter. This can be linked to the findings in Section 6.5.4 which found that increased flexibility of arrival times did not produce a large increase in match rates. Both Figure 6.17 and Figure 7.5 suggest that large groups of individuals seeking to arrive at similar times are conducive to the effective operation of a RSS.

7.4 Goodwill Model Results

To carry out this phase of analysis, the six models previously described for the Original Models are used again. The goodwill scoring system as described in Section 7.2.2 was applied to these models.

7.4.1 Preliminary Analysis

Before examining the economic and environmental impacts of the model, the results are briefly examined, in order to gain an understanding of how the Goodwill Score affects the result. The 2%, 5% and some 10% models are run over a 200 day time period, which allows for a sustainable pool of ride sharers to emerge. Per the discussion in Section 6.5, the results for models with a high number of registrants and a high number of matches take considerably longer to calculate than other models, therefore some 10% are run over a 100 day time period in order to reduce calculation time. The change in the Active Population after this point (shown in Figure 7.4 (c) and Figure 7.5 (c)) is small and therefore it is not believed that this will greatly affect the results.

Each run begins on Day 1 with each commuter having a Goodwill Score of 1, and each run continues for up to two hundred days, which is shown on the x-axis. The goodwill score of each commuter changes with respect to their success in finding matches on previous days, and thus their status as an active participant may change. Figure 7.6 presents results for the Static (FMA) models and Figure 7.7 presents results for the Dynamic models. Each sub plot (a – c) presents three lines: the percentage of active participants, the match rate and the participation level.

The participation level is the percentage of commuters who register on each day of operation and is included in each sub-plot for illustrative purposes. The active population is the percentage of original registrants (N=205,028) who have goodwill scores greater than zero on the day of operation in question. Figure 7.6 and Figure 7.7 illustrate that the active population falls rapidly in the initial phase of the models, and then stabilizes at point approximately equal to the models match rate on Day 1. The stabilisation happens in the time period just after each commuter has registered twice, i.e. at the point in time when we expect most commuters to have a goodwill score of zero.

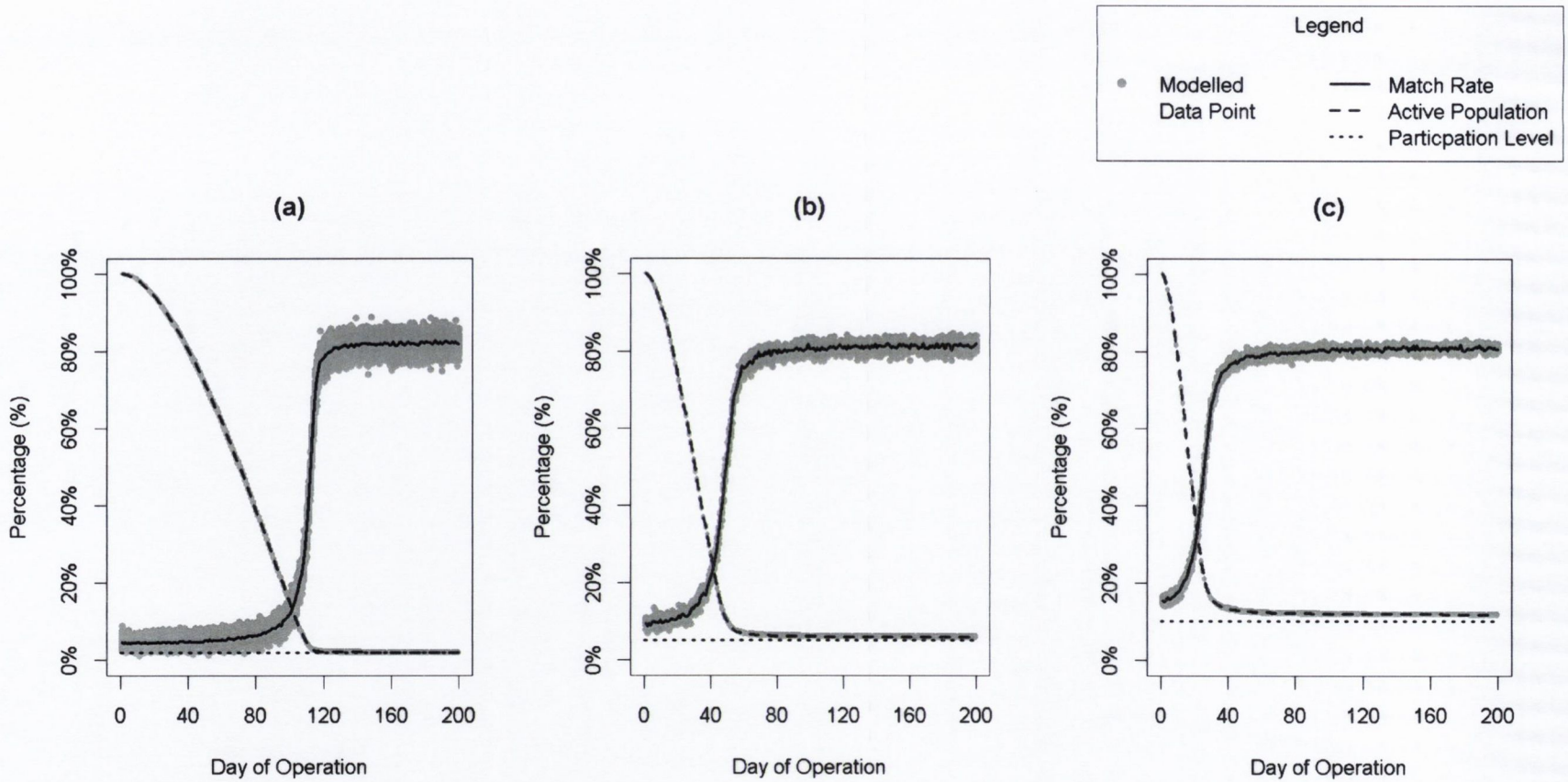

Figure 7.6: Stabilisation of Static (FMA) Models at (a) 2% Participation, (b) 5 % Participation and (c) 10% Participation

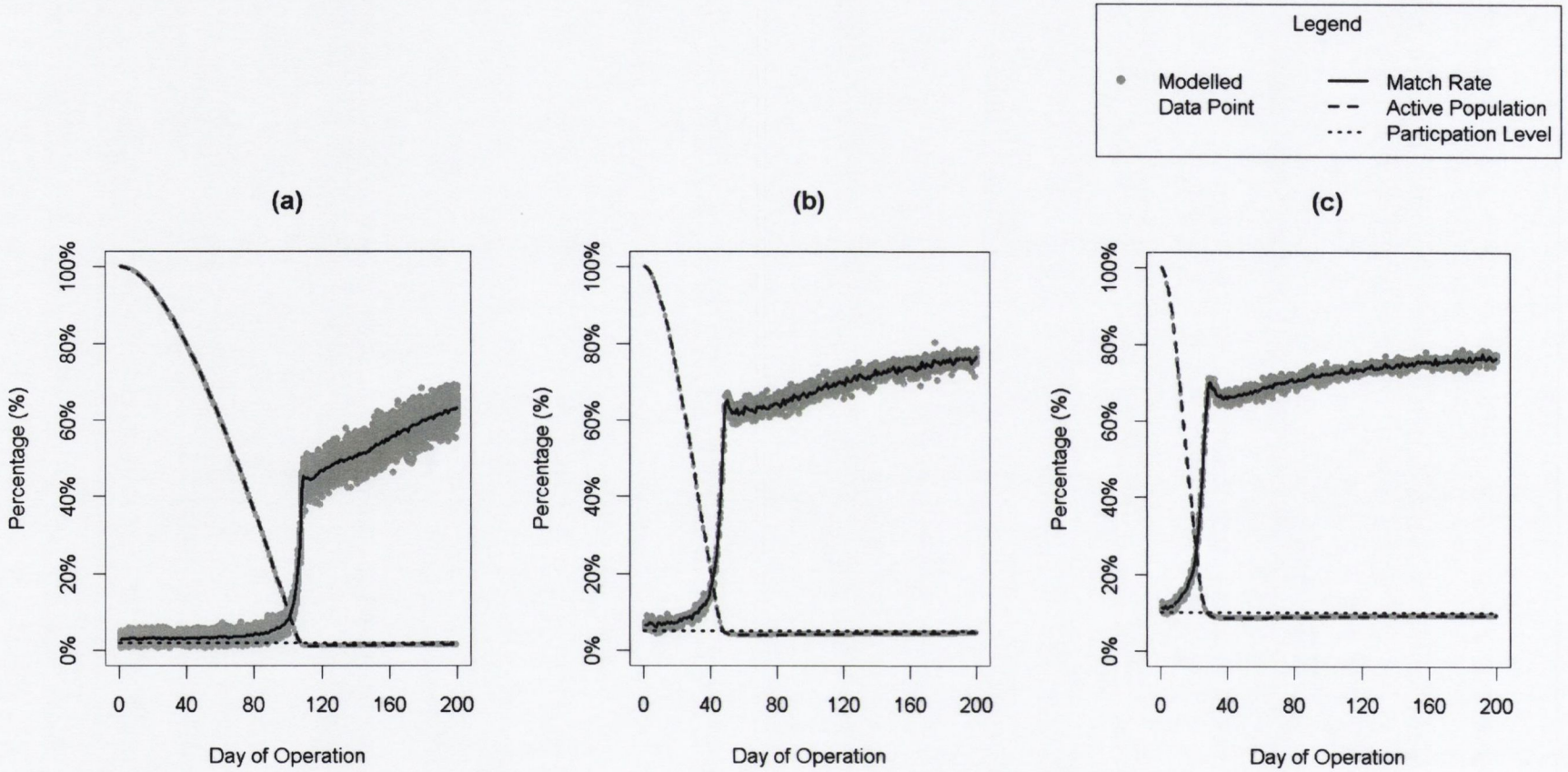

Figure 7.7: Stabilisation of Dynamic (DMA) Models at (a) 2% Participation, (b) 5 % Participation and (c) 10% Participation.

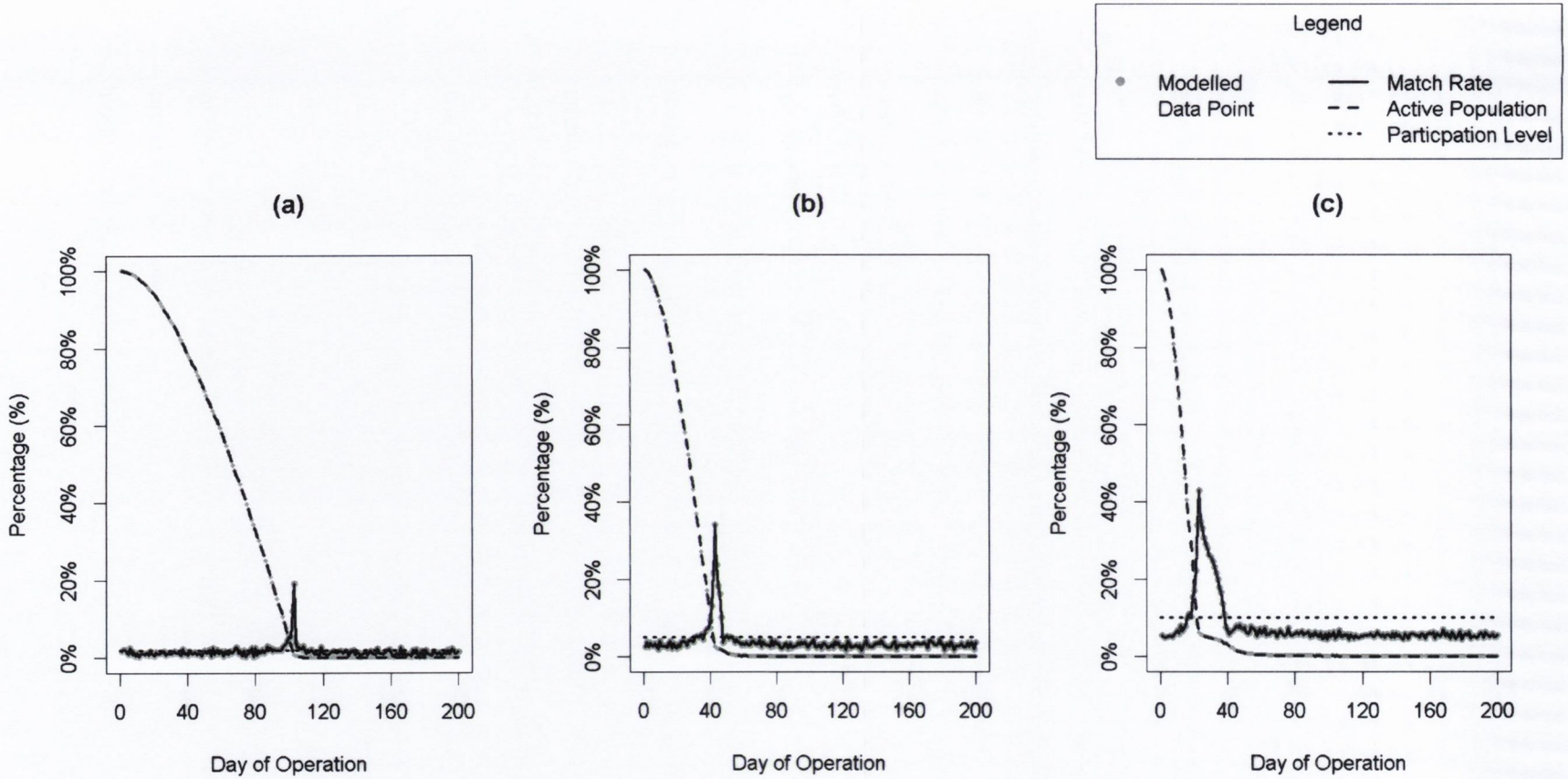

Figure 7.8: Stabilisation of Static (FMA) Models at (a) 2% Participation, (b) 5 % Participation and (c) 10% Participation when $Dist_H$=$Dist_W$=0.5km and $Dist_T$=0.75km

For the Static (FMA) Models, the active population stabilises at a point just above the participation level, therefore no commuters with a zero or negative goodwill score participate. For the Dynamic (DMA) Models, this stabilization occurs when the active population is just below the participation level. After stabilization the model therefore uses a small number of commuters with zero or negative goodwill scores each day. The model has therefore partially failed, however as some of these commuters successfully find matches and consequently re-enter the active population, the model remains stable at a high match rate.

As in previous graphs, the match rate is the proportion of registrants who successfully identify a match as either a driver or passenger on a given day of the model. Between the start of the model and the region of stabilization, the match rate gradually increases from that found under the Original Models described in Section 7.3. As the model stabilizes the match rate rapidly increases. For the Static (FMA) Models, where the active population is greater than the participating population, it increases immediately to its maximum value, of approximately 80%. For the Dynamic (DMA) Models, which partially fail, a rapid increase again occurs as the model stabilizes. This rapid increase is then followed by an initial sharp drop and a more gradual, but still relatively rapid increase as the actively participating population increases due to the addition of previously unsuccessful registrants.

For comparative purposes, a model which wholly fails is shown in Figure 7.8. This represents a model with narrower constraints, i.e. $Dist_H$=$Dist_W$=0.5km and $Dist_T$=0.75km. In this model the active population at stabilisation is well below the participation level, the active population drops to zero and the match rate falls to the same match rate as provided on Day 1.

The economic and environmental analysis impacts of these large changes to the match rate are analyzed in the next section.

7.4.2 Economic and Environmental Analysis

To estimate the economic and environmental impacts of a RSS whose customers act in accordance with the Goodwill Model, we take the results from Days 150 – 200 of each model and average them to calculate an appropriate result as little change occurs in the active population during this period. The results of this process are presented in Table 7.4 below.

Table 7.4: Detailed Economic and Environmental Results: Goodwill Models on Morning Commute Journeys in County Dublin

	Static			Dynamic		
	2%	**5%**	**10%**	**2%**	**5%**	**10%**
Registrants Per Day	4101	10251	20503	4101	10251	20503
Daily Participation Characteristics						
Drivers						
Unmatched	42.8	181.1	374.9	491.7	746.5	1408.9
Matched	1324.2	3235.9	6459.1	874.3	2672.5	5424.1
Drivers w/1 Passenger	*786.5*	*1833.9*	*3736.9*	*431.2*	*1165.4*	*2352.4*
Drivers w/2 Passengers	*358.2*	*927.1*	*1827.5*	*242.1*	*748.3*	*1535.8*
Drivers w/3 Passengers	*179.5*	*474.9*	*894.7*	*201.1*	*758.8*	*1535.9*
Passengers						
Unmatched	692.7	1721.3	3593.0	1182.7	1778.4	3366.1
Matched	2041.3	5112.7	10076.0	1552.3	5051.6	10303.9
Match Rate (Total)	82.1%	81.4%	80.6%	59.2%	75.3%	76.7%
Individual Characteristics						
Distance Travelled by:						
Average Registrant (km)	*3.8*	*4.2*	*4.7*	*4.6*	*4.3*	*4.6*
Matched Passenger (km)	*3.8*	*4.1*	*4.6*	*3.5*	*3.9*	*4.3*
Average Passenger Trip Cost	€1.03	€1.06	€1.11	€1.00	€1.04	€1.08
Average Driver Trip Income	€1.26	€1.35	€1.39	€1.41	€1.58	€1.65
Environmental Impacts (Total Per Annum)						
1000 kg CO_2 Saved	288.4	797.8	1763.0	201.7	745.8	1681.6
Economic Impacts (Total Per Annum)						
Total Passenger Spending on RSS	€525,334	€1,366,019	€2,819,224	€387,719	€1,321,405	€2,802,155
Gross Passenger Savings						
Total	*€1,028,746*	*€2,845,531*	*€6,287,958*	*€719,408*	*€2,660,196*	*€5,997,728*
Operational	*€348,043*	*€962,694*	*€2,127,328*	*€243,388*	*€899,991*	*€2,029,138*
Net Passenger Savings						
Total	*€503,412*	*€1,479,512*	*€3,468,734*	*€331,688*	*€1,338,791*	*€3,195,573*
Operational	*-€177,291*	*-€403,325*	*-€691,896*	*-€144,331*	*-€421,413*	*-€773,017*
RSS income	€105,067	€273,204	€563,845	€77,544	€264,281	€560,431

Table 7.4 illustrates the greater economic and environmental impacts which occur under the Goodwill Model. The average number of registrants achieving a match is higher at 2% participation than it was at 10% under the Original Models. The impact of the increased match rate is somewhat negated by the lower average distance travelled by matched passengers.

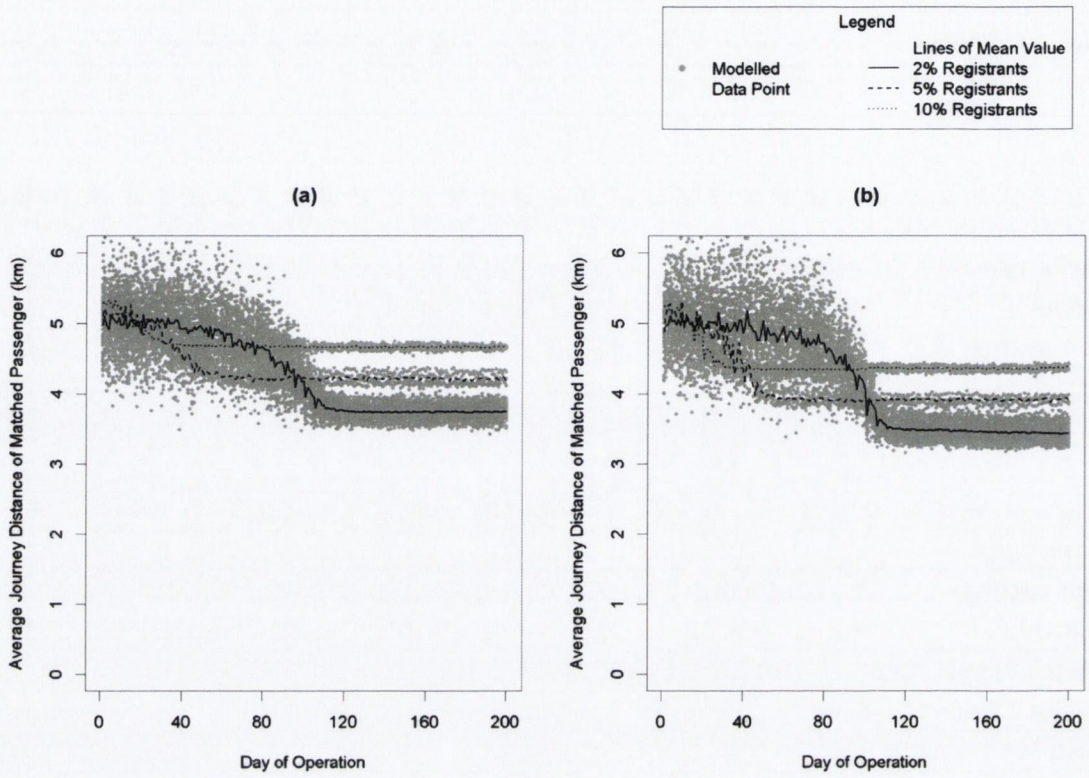

Figure 7.9: Average Journey Distance of Matched Passengers by Day of Operation for (a) Static and (b) Dynamic Goodwill Models.

Figure 7.9 explores this more fully by presenting the average distance travelled by a matched passenger on each day of operation for each version of the model. It illustrates that as the pool of active participants' falls and the match rate increases, the average matched passenger distance falls. In short, passengers with shorter journeys are more likely to identify matches than those with longer journeys.

It is also worth noting that while average passenger distance (and consequently spending) falls, the income of the average driver increases. This is because the proportion of drivers achieving a match with 2 or more passengers' increases significantly from the levels achieved within the Original Models.

7.4.3 Geographic and Time Period Analysis

In this section we analyze the features of individual journeys which make it both more and less probable that an individual will successfully identify a match under the Goodwill Models. As with the Original Models, the distribution of individual match rates is first examined.

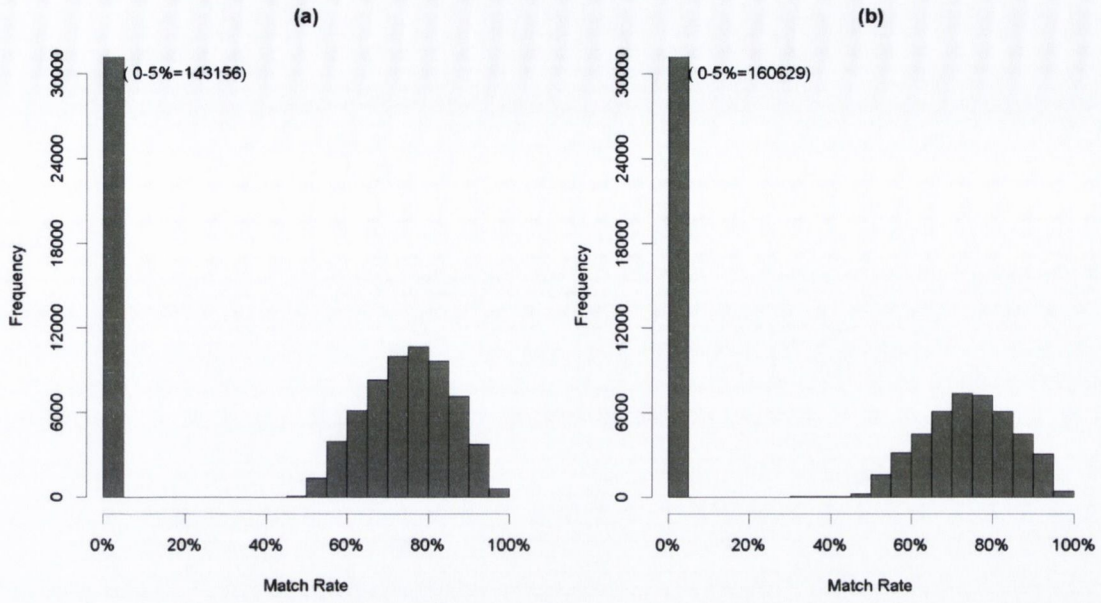

Figure 7.10: Proportion of Registrant Population in Each Individual Match Rate Band for (a) Static (FMA) and (b) Dynamic (DMA) Goodwill Models at 10% daily participation

Figure 7.10 presents a frequency distribution of these individual match rates of individuals remaining in the active population on Day 200 of the 10% participation (a) Static (FMA) and (b) Dynamic (DMA) Goodwill Models. Figure 7.10 can be directly compared with Figure 7.2.

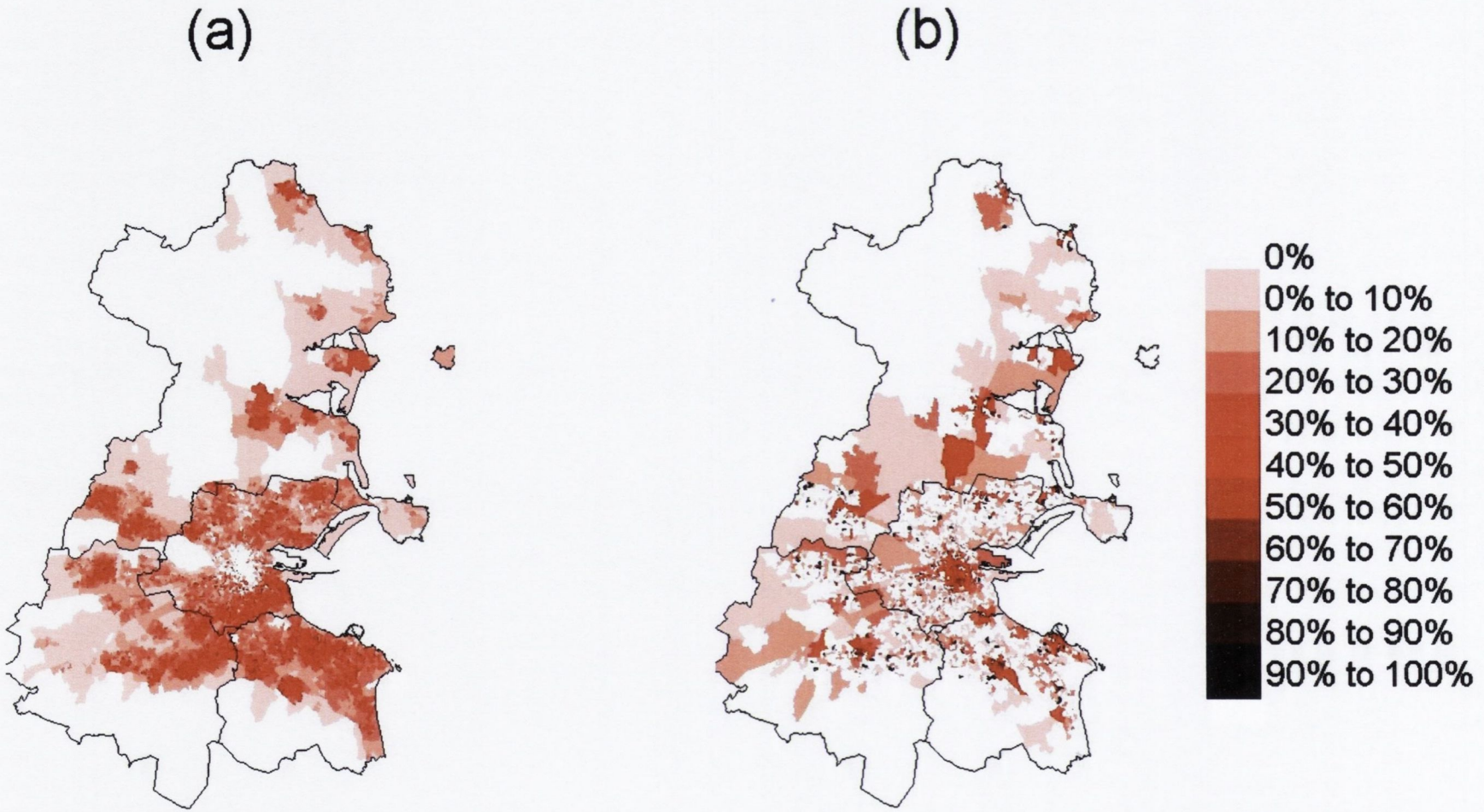

Figure 7.11: Percentage of Participants, by (a) Small Area of Residence and (b) Small Area of Work, Remaining in the Active Population after 100 days under the Static Model at 10% Participation.

It illustrates that under the Goodwill models the majority of potential registrants (N=205,028) have match rates below 5%, however in contrast to the original models, those who remain in the active population typically achieve individual match rates well above 60%.

Figure 7.11 shows the percentage of commuters in each small area who remain as part of the active population at day 100 in at least one of fifteen runs of the 10% Static Goodwill model. Similar maps (not shown) were generated for each of the other 5 variants of the model. These maps display lower rates of successful matching, but similar patterns geographically. Figure 7.11 illustrates that under the Goodwill Model, large areas of the county have no active ride sharing population, and successful ride sharers are more geographically concentrated. In particular certain work locations could potentially have over 80% of workers participating successfully and regularly in the RSS. This suggests that as the RSS rolls out, it should specifically target certain locations for registrants, possibly even refusing to allow those outside these locations to register and seek matches.

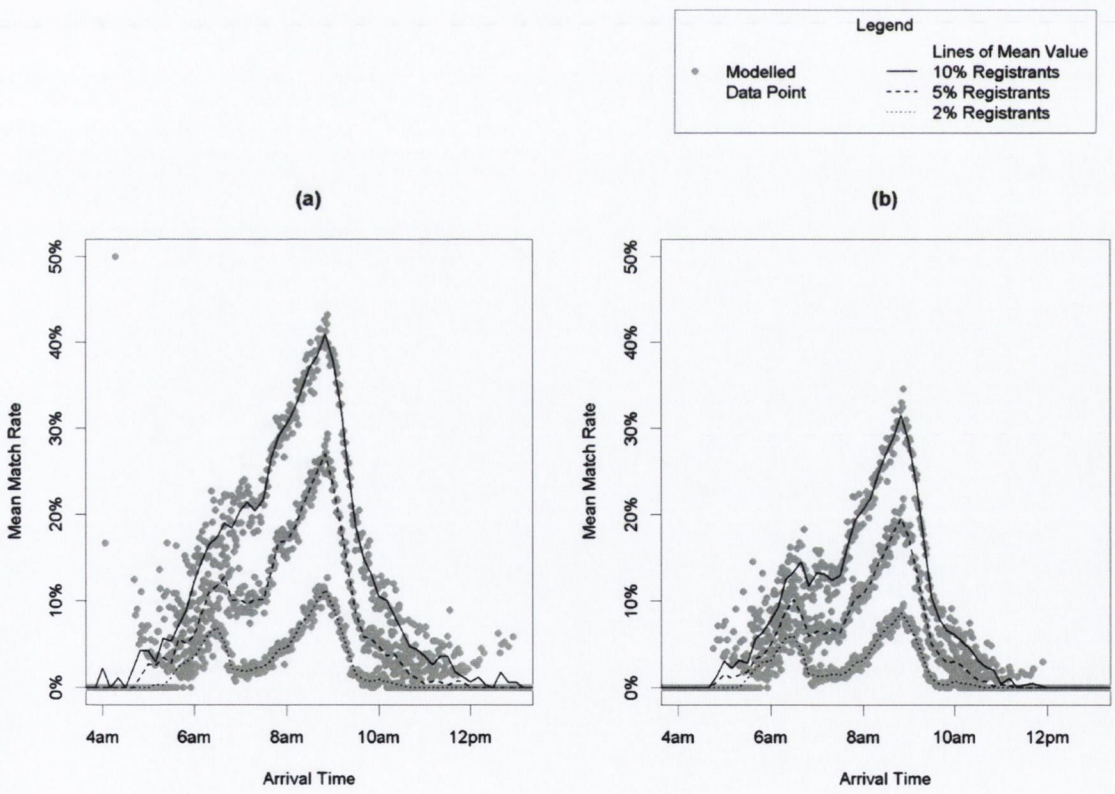

Figure 7.12: Goodwill Models: Average Match Rate by Desired Arrival Time at Place of Work

Figure 7.12 illustrates when these successful ride sharing participants seek to arrive at work. The peak period for successful ride sharing remains between 8am and 10am with a small earlier peak

around 6.30am. As with the geographical analysis, this suggests that as the RSS rolls out, it should specifically target registrants with specific characteristics, in this case characteristic arrival times.

7.5 Targeted Rollout Models: Dun Laoghaire Town Centre

To examine the Targeted Rollout Model, the use of a RSS by the commuter driver population working within 2km of DLTC is evaluated. The potential registrant population is therefore comprised of 4,980 commuters. In the first section the match rates achieved under a variety of Original Models (described in Section 7.2.1) are evaluated. This is followed by the analysis of a selected set of Goodwill Models (described in Section 7.2.2) in the second section.

7.5.1 Original Models: Exploratory Analysis of DLTC

The smaller potential registrant population enabled a comprehensive exploratory analysis to be undertaken. Due to the smaller populations, the use of batches with Dynamic models creates difficulties, e.g. with 250 registrants, 5 batches and a D/P of 0.1, only 6 drivers register with the early batches, leading to difficulties with the clustering mechanism. This exploratory analysis was therefore only undertaken for the Static (FMA) based model. Three sets of constraints (Case A, Case B, & Case C as described in Section 6.7) arising from the Flexible Matching Algorithm are used as the basis for the exploratory analysis.

Table 7.5: DLTC BCMA Constraints

	Sub-Plot			
	(a)	**(b)**	**(c)**	**(d)**
$Dist_H$ (km)	0.5	0.625	0.75	1
$Dist_W$ (km)	0.5	0.625	0.75	1
$Dist_T$ (km)	0.75	0.9375	1.25	1.5
T (minutes)	15	15	15	15
Seat Capacity	3	3	3	3

These are combined with four sets of model constraints based on the Base Case Matching Algorithm. These four sets of model constraints were chosen to illustrate slightly differing levels of willingness to undergo geographic inconvenience. The four sets used are summarised as (a), (b), (c) and (d) as described in Table 7.5. For each of the resulting 12 combinations, differing levels of population participation were tested, i.e the number of daily registrants was varied from 5% (249) to 50% (2490) of the potential registrant population.

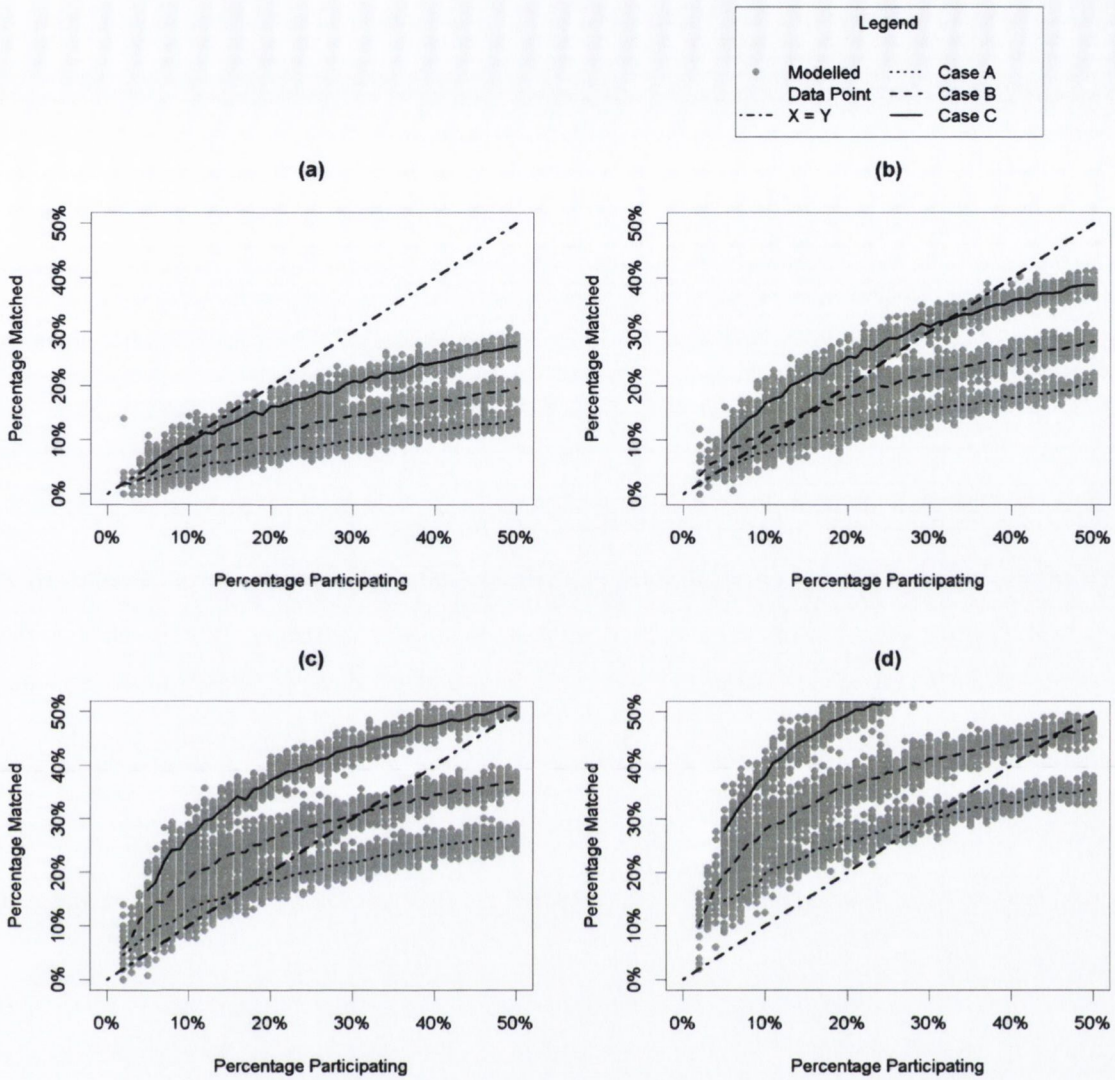

Figure 7.13: DLTC modelled per Table 6.5 at different rates of daily participation

Figure 7.13 presents the results of this exploratory analysis. In each panel of Figure 7.13, the percentage of the available registrant population registering on a given day is varied along the X-axis. The match rate is then plotted on the Y-axis. As expected, as the BCMA constraints are relaxed (moving from panel (a) to panel (d)), the match rate increases. Similarly as the proportion of flexible passengers increases (moving from Case A, to Case B & Case C) the match rate also increases. This is as expected from the results presented in Chapter 6. A direct comparison between the results presented for DLTC in panel (c) and the results presented for Dublin County in Chapter 6 can be made. The match rates of panel (c) at 10% population participation are 13.0%, 18.7% and 26.7% for Case A, B and C respectively. The BCMA constraints shown in panel (c) are identical to those used for Case 3 in Chapter 6. Per Table 6.3, Table 6.4 and Table 6.5, the Dublin

County match rates for Case A, B and C are 11.2%, 15.5% and 20.2% respectively. It therefore seems that the Original Model match rates for DLTC follow the same pattern but are higher than those for Dublin County.

7.5.2 Goodwill Models: DLTC

From the range of exploratory Goodwill Models conducted as part of this thesis (both presented and not) a potential relationship between the match rate under the Original Models and the active population after model stabilization of the Goodwill Models was observed. Using the DLTC case study, this relationship is now further examined.

A fourth line, labelled X=Y, representing the point at which the match rate is equality to the participation rate, is included on each of the sub-plots presented in Figure 7.13. The DLTC version of the Goodwill model is run over 200 days, using 20% population participation and the 12 sets of constraints described for Figure 7.13. Table 7.6 summarises the results of these 12 models. The result is categorised as a success if the active population on Day 200 is above 20% of the potential registrant population (996). If the number of potential registrants with a goodwill score at or above zero is greater than 996, the result is classified as a Partial Failure. The remaining cases are classified as a Failure.

Table 7.6: Results of Exploratory Goodwill Models for DLTC Case Study

	$Dist_T$	Case	Original Match Rate	Day 200 Results					
				Active Population	Daily Match Rate	Under Zero	At Zero	Active	Result
	0.75	**A**	7.4%	0.1%	7.6%	4967	8	5	Failure
(a)	**0.75**	**B**	11.2%	17.0%	66.1%	4022	110	848	Failure
	0.75	**C**	16.2%	20.4%	92.0%	0	3964	1016	Success
	0.94	**A**	11.8%	0.7%	13.1%	4884	62	34	Failure
(b)	**0.94**	**B**	18.0%	19.9%	79.8%	2008	1981	992	Partial Fail
	0.94	**C**	25.4%	28.7%	89.2%	0	3549	1432	Success
	1.25	**A**	18.7%	18.0%	63.4%	3700	384	897	Partial Fail
(c)	**1.25**	**B**	26.3%	24.6%	81.5%	0	3753	1227	Success
	1.25	**C**	37.2%	37.6%	89.8%	0	3106	1874	Success
	1.50	**A**	26.5%	20.3%	75.4%	31	3938	1011	Success
(d)	**1.50**	**B**	36.0%	33.7%	80.3%	0	3302	1678	Success
	1.50	**C**	49.4%	49.1%	89.4%	0	2533	2447	Success

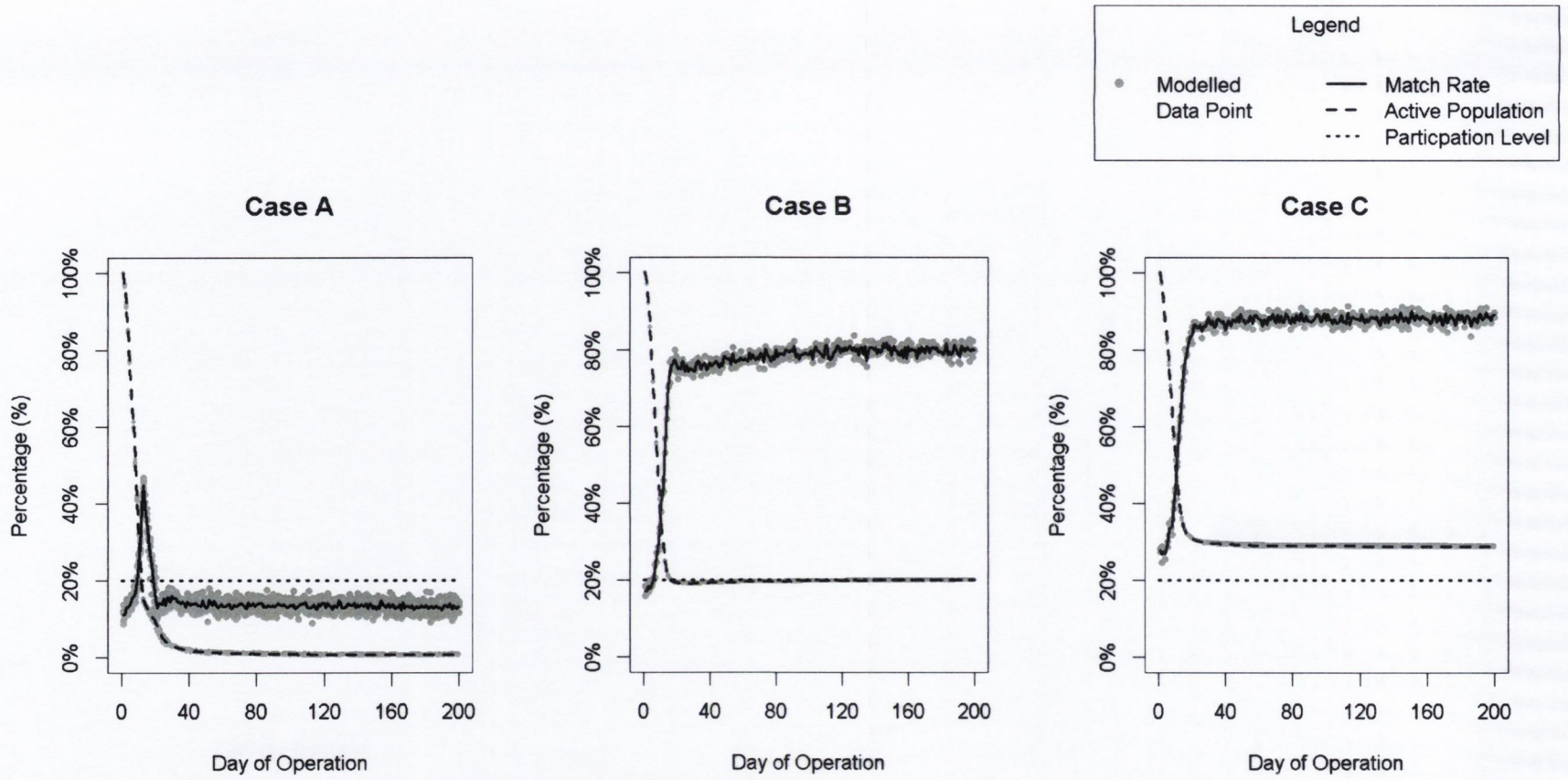

Figure 7.14: DLTC: Stabilisation of Static (FMA) Models at 20% Participation for Case A, B & C when $Dist_H$=$Dist_W$=0.625km and $Dist_T$=0.9375km

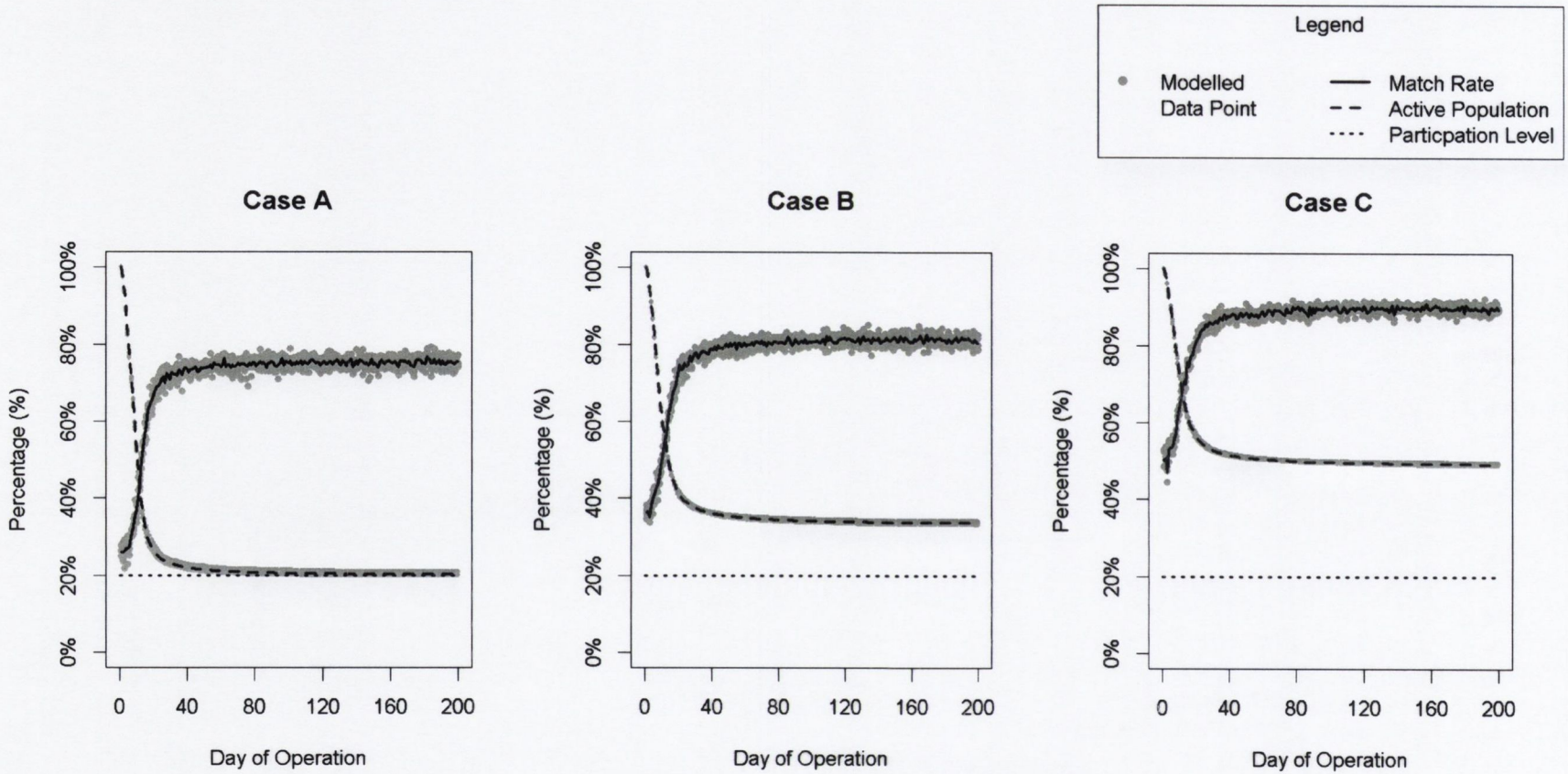

Figure 7.15: Stabilisation of Static (FMA) Models at 20% Participation for Case A, B & C when $Dist_H$=$Dist_W$=1km and $Dist_T$=1.5km

To illustrate how each case presents graphically over the 200 Day time period, Figure 7.14 presents the results for the set of constraints described as (b) in Table 7.5. This illustrates a failure (Case A), partial failure (Case B) and successful (Case C) model. Figure 7.15 presents the results for the set of constraints described as (d) in Table 7.5, i.e. three successful models.

In terms of predicting model pass or failure based on the initial conditions, no clear rule emerges. However in general, if the original match rate is greater than 20% (i.e. the participation level), the model succeeds, where the original match rate is less than 15% the model fails, and where the original match rate is between 15% and 20%, the model may partially fail or succeed.

Examining this in more detail, for $Dist_T$ = 0.75km, under Case C, the model succeeds with an original match rate of 16.2%, however for $Dist_T$ = 0.9375 under Case B, the model partially fails with a higher original match rate (18.0%). Similarly for $Dist_T$ = 1.25, under Case A, the model partially fails with an original match rate of 18.7%. Examining the Active population the (b)-B model is in fact very close to succeeding, in contrast the (c)-A model is much closer to failing. This suggests that the presence of flexible registrants may again enable a RSS to succeed when it otherwise might not.

On Day 200, most of the models have an active population which is close to the daily participation level. For these model conditions, if the RSS is to operate successfully, all those likely to achieve matches must register on every working day. This is unlikely to occur; however Figure 7.15, Case C presents an active population which is more than double the daily participating population. Under these conditions, if each registrant participates 2 – 3 days per week, the model will continue to operate successfully, i.e. this model describes a potentially viable ride sharing service.

Finally in this section, Table 7.7 presents the Economic and Environmental savings of the DLTC, run per the criteria used in Table 7.4, Section 7.4, but with population participation levels of 10%, 20% and 50% due to the restricted potential registrant population. This is equivalent to Case (c)-B as presented in Figure 7.13 and Table 7.6. Comparing the results to those presented for the original models, it is clear that 498 registrants (10% DLTC) with appropriate journey characteristics participating daily in a small area provides a higher income to the RSS and higher CO_2 savings than 4,101 (2% Dublin County) random individuals participating across a wider area. Furthermore the need for daily commuter parking in the DLTC area is reduced by 245 spaces.

Table 7.7: Economic and Environmental Savings of DLTC model

	Static (FMA)			Dynamic (DMA)		
	10%	**20%**	**50%**	**10%**	**20%**	**50%**
Registrants Per Day	498	996	2490	498	996	2490
Daily Participation Characteristics						
Drivers						
Unmatched	12.0	21.2	78.2	27.9	60.2	248.7
Matched	154.0	310.8	751.8	138.1	271.8	581.3
Drivers w/1 Passenger	*85.2*	*174.3*	*472.2*	*60.3*	*115.3*	*276.1*
Drivers w/2 Passengers	*46.1*	*91.2*	*199.4*	*38.6*	*76.5*	*166.5*
Drivers w/3 Passengers	*22.8*	*45.3*	*80.3*	*39.3*	*80.0*	*138.6*
Passengers						
Unmatched	86.4	171.3	548.2	69.9	141.9	607.7
Matched	245.6	492.7	1111.8	262.1	522.1	1052.3
Match Rate (Total)	80.2%	80.7%	74.8%	80.4%	79.7%	65.6%
Individual Characteristics						
Distance Travelled by:						
Average Registrant (km)	*3.6*	*4.2*	*5.2*	*3.5*	*4.0*	*5.3*
Matched Passenger (km)	*3.6*	*4.2*	*4.9*	*3.5*	*3.8*	*4.4*
Average Passenger Trip Cost	€1.01	€1.07	€1.14	€1.00	€1.03	€1.09
Average Driver Trip Income	€1.29	€1.35	€1.35	€1.52	€1.59	€1.58
Environmental Impacts (Total Per Annum)						
1000 kg CO2 Saved	33.5	77.4	206.7	34.3	75.3	175.4
Economic Impacts (Total Per Annum)						
Total Passenger Spending on RSS	€62,379	€131,944	€319,209	€65,649	€135,396	€288,641
Gross Passenger Savings						
Total	*€119,340*	*€275,883*	*€737,298*	*€122,429*	*€268,655*	*€625,728*
Operational	*€40,375*	*€93,336*	*€249,441*	*€41,420*	*€90,891*	*€211,695*
Net Passenger Savings						
Total	*€56,961*	*€143,938*	*€418,089*	*€56,780*	*€133,258*	*€337,087*
Operational	*-€22,005*	*-€38,608*	*-€69,768*	*-€24,229*	*-€44,506*	*-€76,946*
RSS income	€12,476	€26,389	€63,842	€13,130	€27,079	€57,728

7.6 Discussion

From the findings of the Goodwill Models and the Original Models both as used for Dublin County and for the DLTC case study, we can make a number of important conclusions.

As the Original Models demonstrate, if the population of registrants is not affected by previous success or failure in identifying matches, then a RSS is unlikely to operate successfully. Under the combination of constraints evaluated, even when 20,000 individuals in Dublin register completely randomly, each individual only has a 1 in 6 chance of achieving a match. Considering the time that each registrant would spend registering and then trying to identify a match, the scenario can be considered unlikely.

To achieve a viable match rate, estimated to be a minimum of 50%, the results of Chapter 6, presented in Table 7.3 suggest that at 5% participation a willingness to detour a combined distance of close to 3km to pick up and drop off locations and registrant flexibility above those of Case B, (i.e. fewer than 1/3rd of registrants restricting their role to driver only and more than 1/3rd of registrants being willing to act as passengers or drivers) would be required. For participation levels below 5%, greater willingness to detour and registrant flexibility will be required.

The need to detour to pick up and drop off locations can be somewhat mitigated if the matching algorithms are expanded to estimate routes for each potential driver, and suitable crossed routes can be identified. However for registrants using the RSS this adds an additional level of complication to the journey, i.e. the need to estimate not only a departure time but also an arrival time at a particular point en-route, which may be affected by traffic. Overall, without a considerably more complex algorithm, a RSS operating in line with the original models is very unlikely to succeed in the Dublin County area.

The Goodwill Models introduce a simplified self-selection mechanism to the registrant population. They demonstrate that if those registering on a daily basis have more suitable journeys, the RSS can operate successfully with a relatively small numbers of users and make a meaningful difference to CO_2 emissions from commuting at higher levels. The higher match rates achieved by the Goodwill Models are important not just for the higher RSS income and CO_2 savings they produce, but for the likelihood of continued participation by registrants. As shown in Figure 7.10, the active population of ride sharers after model stabilisation have typical match rates around 80%, presenting a potentially worthwhile investment of time registering and organising matches.

The DLTC case study then evaluates whether a RSS could successfully operate with a restricted clientele, and the results suggest that such an approach is preferable to a wider scheme. The selection of a favourable location resulted in higher match rates under the original models. In spite of lower absolute levels of participation, the daily participation of higher proportions of the potential registrant population led to the goodwill models stabilising quickly. This means that a

pool of regularly successful registrants emerges more rapidly and thus the RSS is profitable at an earlier date.

The relationship between the original model match rate and the active population is also important. Knowledge of this relationship enables an RSS to quickly identify whether the behaviour of registrants in an area is conducive to successfully establishing a service. From the knowledge of the impact of behavioural constraints gained in this Chapter and Chapter 5, the RSS should then be able to react appropriately, increasing the chances of success.

Taken together, this chapter and Chapter 5, add greatly to the understanding of Ride Sharing Services, particularly in relation to understanding how, where and under what registrant behavioural conditions a successful RSS might be established.

7.7 Conclusion

The results of these models again suggest key areas of focus for practitioners and policy makers seeking to establish a successful ride sharing service. These are

1) Undertake a targeted rollout of the RSS, limiting registration to commuters with specific characteristics, i.e. those registering should seek to commute within a narrow range of desired arrival times or commute to a specific geographic work location or commute from a specific geographic home location or a combination of these characteristics.
2) Registrants who successfully identify matches should be incentivised to re-register frequently.

8 CONCLUSIONS

8.1 Introduction

This thesis examines approaches to improving the sustainability of transport by reducing reliance on private vehicles. To accomplish this objective the thesis presents an analysis of two separate but related issues – car sharing and ride sharing. Each set of analyses is therefore treated separately and an in-depth discussion of the results found is provided at the end of the appropriate chapter.

This chapter provides a brief summary of the work described in this thesis and draws together the main conclusions reached in each chapter. It then critically assesses the work as a whole and identifies areas for further research.

8.2 Summary of Thesis

The aim of this thesis is to evaluate the sustainability impacts of two methods of reducing reliance on private vehicles, using Dublin and by extension Ireland, as a case study. This summary identifies how the three objectives and four aims outlined in section 1.6 have been met.

Aim 1 was to conduct a detailed literature review of car sharing, ride sharing. This objective is met in Chapter 1 and Chapter 2. Chapter 1 provided an introduction to the concepts of sustainability and sustainable development. Chapter 2 discusses the literature on two methods of reducing reliance on private vehicles, namely ride sharing and car sharing. The literature linking travel, wellbeing and private vehicles is also discussed. In each of the three areas of literature reviewed, gaps in the research are identified.

Aim 2 was to achieve a better understanding of the sustainability of individual travel patterns in Ireland, including spending on domestic transport, the environmental impact of domestic transport and the relationship between travel patterns and individual wellbeing. The data sources discussed in Chapter 3 and survey analysis carried out in Chapter 4 highlight the high cost of private vehicles and the high reliance residents of Ireland have on private vehicles. Data presented in Chapter 3 shows that while Dublin outperforms the rest of the country in terms of a sustainable modal split, with 61% of all trips being made in a private car, and 75% of household owning a car, there is an over reliance on car travel, and considerable room for improvement. These findings are reinforced by the results of the survey, which show that for adults in Ireland,

cars are the main means of travel, and that this over-reliance is particularly severe among the working population.

The analysis of the costs and carbon dioxide emissions of survey respondents shows a strong link between car ownership and increased spending on travel. Car owners spend more on travel annually and their cost per km travelled is higher than non-car owners. Car owners also have higher levels of carbon dioxide emissions per km and per annum than non-car owners. Section 4.4, examines the link between social sustainability and the use and ownership of private vehicles. The analysis is accomplished by using the wellbeing results from the survey described in Chapter 3 to examine the link between wellbeing and travel patterns, focusing both on private vehicle usage and on broader travel patterns. This analysis identifies no relationship between private vehicle ownership or usage and wellbeing. A relationship is identified between cycling and wellbeing however further research is needed to investigate the nature of this relationship.

In Chapter 5 the first objective and third aim are addressed. An analysis of the potential of a CSS to reduce the environmental and economic impacts of car ownership and travel was carried out. This was accomplished by using Census 2011 data discussed in Section 3.2 and existing literature on the effects of CSS membership discussed in Section 2.2. These sources are used in conjunction with the results of the survey presented here to model the uptake and usage of a CSS in Ireland. Based on the model of uptake and usage environmental and economic impacts are calculated.

In Chapter's 6 and 7 the second objective and fourth aim are addressed. These chapters describe the analysis of the potential of a RSS to reduce the environmental and economic impacts of those commuting to work by car. This is accomplished by developing and implementing model algorithms which evaluate different aspects of the RSS and user behaviour. The results provided by the models are then used in conjunction with data sources (including the survey carried out in Chapter 3) which describe the costs and environmental impacts of travel, to calculate the environmental and economic impacts of a RSS operating in the Dublin area.

8.3 Impact of the Research

The main impacts of this research are in the areas of ride sharing and car sharing. Each of these areas is now discussed in turn.

8.3.1 The Potential of Car Sharing

The study described in Chapter 5 of this thesis evaluates the potential of CSS in Dublin and in Ireland. The study presents multiple alternative scenarios which examine the geographic, financial and environmental factors influencing CS adoption and use. The scenarios were developed using observations from existing CSS in other countries. Some observations from the small scale CSS, GoCar, operating in Ireland have also been used to compare the travel behaviour change among CSM in Ireland and elsewhere. These scenarios were applied to the available and collected travel information of the Irish population to estimate the potential impact of introducing CSS in Ireland. The travel information was collected through an activity diary based survey administered to over 2,500 respondents. Information available through the census and National Travel Survey data of Ireland was also utilised.

The study showed CSS holds immense potential in terms of cost savings to members, reduction of travel related CO_2 emission and increased share of sustainable modes of travel. In almost all the scenarios designed in the study, financial savings were estimated for members of CSS. This is expected to be the most influential factor in attracting individuals to join CSS. For both policy makers and practitioners the key finding is with regard to the differences between the early roll out and middle roll out phases. Where a CSS operates only in early roll out areas, the projected membership in Dublin is between 5,344 and 7,481. With expansion to Middle Rollout areas the projected membership is between 199,866 and 279,813, representing 21% - 29% of the population in the serviced areas. This difference in membership levels between early and middle roll out phases results in approximately a 30 fold difference in projected CO_2 savings.

The study therefore provides a possible business case of CSS through public or private investment or through public-private partnerships. Such partnerships should be supported by local government policy facilitating car sharing stations and parking in the early and middle roll out areas identified in Figure 5.2.

Each of the findings made from the analysis of the CSS model makes a contribution to the knowledge of car sharing and thus to the chances of a CSS being successfully established in Dublin and elsewhere.

8.3.2 The Potential of Ride Sharing

The investigation of the potential of ride sharing makes a number of strong contributions to the body of research on ride sharing. In Chapter 6 several models of ride sharing are built and

evaluated. The models are designed implemented using open source software, and require three inputs for each potential registrant – origin (as an X,Y co-ordinate), destination (as an X,Y co-ordinate) and a desired arrival time. This information is readily obtainable to many organisations or event co-ordinators who might seek to establish a RSS. In contrast to some previous research in the area which uses commercial optimisation software (e.g. Agatz, 2011) the models designed as part of this thesis can therefore be easily understood and readily used to carry out further analysis of RSS operation by other researchers.

In evaluating the four models in Chapter 6 several contributions are made which will be of use to practitioners. The analysis of the BCMA identifies two factors as being key to successfully promoting a RSS, these are registrants willingness to undertake detours to arrange convenient pick-ups and drop offs and the number of people registering with the RSS on a daily basis. Factors found to be less important included registrants willingness to be flexible with their arrival time at work and the willingness of drivers to carry more than one passenger.

The analysis of the FMA finds that the willingness of registrants to partake of matches as either a driver or a passenger has a large influence on the number of matches which can be achieved. Under ideal conditions all registrants are willing to act as either driver or passenger. When this is not the case, the analysis finds that in general a shortage of individuals seeking a driver match and an excess of individuals seeking a passenger match is preferable.

The analysis of the SMA illustrates how registrant preferences with respect to those with whom they share a journey may impact on the success or failure of a RSS. The analysis is somewhat hampered by a lack of revealed preference and stated preference in the area, however the models used demonstrate an approximately linear relationship between reluctance to share with dissimilar people and the proportion of registrants identifying a match. The algorithms developed can also be readily adapted to reflect different social matching preferences.

The analysis of the DMA demonstrates that care must be taken if matching is to be carried out at several intervals throughout the day. Dynamic matching tends to reduce the overall match rate, particularly when registrants arrive in small groups (many batches). We find that this effect is exacerbated if a pool of drivers is not readily available early in the dynamic matching process. In practice, the negative impacts of dynamic matching may also be mitigated by increased participation.

Each of the findings made from the analysis of the four Chapter 6 models makes a contribution to the knowledge of ride sharing and methods of increasing the changes of a RSS being successfully established.

Chapter 7 builds on the work carried out in Chapter 6, by simulating real world conditions and calculating the potential environmental and economic impacts of a RSS. This provides information that can be usefully applied to developing policy and an economically viable RSS. By comparing the Original Models and the Goodwill Models, the importance of the right registrants participating in the service is highlighted. If the right registrants (i.e. those remaining in the active population) can be incentivised to register with the RSS regularly, the economic and environmental calculations show that a RSS can contribute to a meaningful reduction in CO_2 emissions while operating as a financially viable business.

The DLTC case study strongly suggests that the most effective way of developing a RSS may be to restrict registration to specific geographic areas and large organisations which have a suitable pool of potential registrants.

For policy makers, the key finding is that of chapter 7, that a ride sharing service is most likely to succeed by restricting registration to specific geographic areas and large organisations which have a suitable pool of potential registrants. Policymakers can therefore assist RSS's by identifying such areas/organisations and providing incentives (designated parking spaces, tax breaks etc.) which encourage the adoption of ride sharing.

Overall the models presented in Chapter 6 and 7 find that practitioners can greatly increase their chances of successfully establishing a ride sharing service by:

1) Allowing and incentivising registrants to register in a flexible role,
2) Incentivising registrants to travel greater distances to achieve a match,
3) Incentivising registrants, particularly drivers, to register in advance of a specific deadline,
4) Restrict registration to specific geographic areas and large organisations which have a suitable pool of potential registrants,
5) Achieving a sufficient number of registrants to allow each registrant a good probability of achieving a match within an appropriate distance.

8.3.3 Comparing Car Sharing and Ride Sharing

The work on car sharing focuses on behavioural change across an individual's travel pattern while the work on ride sharing focuses exclusively on an individual's commute journey. The results are not therefore directly comparable, however some observations may be made.

The projected CO_2 saving from 10% (20,503) of the driver commuter population of Dublin participating in ride sharing daily is 1.7kt under the dynamic and static goodwill models. Similarly for 2,490 commuter drivers in Dun Laoghaire the projected saving is 0.2kt. Such savings are not dissimilar to that projected in the early roll out phase for car sharing, which projects a CO_2 saving of 0.4 – 1.8kt depending on the characteristics of the CSMs.

At the middle and later roll out stages, car sharing offers a 30 fold increase in the potential for CO_2 savings, however this comes at the cost of much higher infrastructural, policy and capital support. In contrast establishing a successful ride sharing scheme can be done at minimal expense through the development of an appropriate smart phone "app" and marketing campaign. A successful ride sharing service operating during peak hours may also induce secondary behavioural impacts such as the sale of a second car or greater use of public transport. Such behavioural changes would result in greater carbon dioxide reductions than are forecast as part of this work.

For policy makers and practitioners, both ride sharing and car sharing are worth pursuing as means to reduce the carbon dioxide emissions of transport. Given a limited budget, ride sharing is simpler to effect, however with financial backing from business investors and suitable policy support car sharing offers much greater scope for carbon dioxide reduction.

8.4 Critical Assessment

Although there are many areas in this thesis which have added to the body of research conducted on car sharing, ride sharing and transport and wellbeing, there are a number of limitations which are summarised below.

The responses to the survey conducted in Chapter 3 may not have been representative of the population due to the use of the internet as a survey tool and the distribution techniques used. This is somewhat mitigated by the use of socio-demographic data provided by the respondents to identify populations of interest. While comparisons with other work in the area e.g. the National Travel Survey (CSO, 2011b) and the National Household Budget Survey 2009-2010 (CSO, 2012e), also suggest the results obtained are reliable, some may argue that alternative and/or additional

data collection techniques should have been used to better ensure a representative sample. This affects both the results presented in Chapter 5 and the results presented in Chapter 7.

In the absence of a car sharing service operating across Dublin, the results of the feasibility analysis conducted in Chapter 5 are necessarily somewhat speculative. However, the principle contribution the work in Chapter 5 makes is the development of a methodology, which enables both CSS and government advisors themselves to estimate the potential of a CSS operating in a specific area.

The ride sharing study outlined in Chapter 6 and Chapter 7 is unique in the literature as it models the real commuter journeys of a large population. While this work has done its best to estimate a range of reasonably feasible behavioural constraints, more real world data on the actual behaviour of ride sharers would of course be both useful and desirable. Of the six models analysed, two in particular – the Social Matching Algorithm and the Goodwill Models would benefit greatly from a more nuanced understanding of ride sharers behaviour. However, both these models involve socio-cultural considerations and if further data is obtained care must be taken as to its wide spread applicability. For instance, the social matching algorithm considers how likely ride sharers are to agree to share a journey with a member of the opposite sex, which some cultures will find wholly unproblematic and other cultures ban entirely. The models described in this thesis therefore illustrate a range of possible scenarios and the algorithms developed allow for the easy implementation of alternative scenarios.

8.5 Areas for Future Research

A number of areas for future research can be readily identified from this thesis.

8.5.1 Car Sharing

In proportion to its market share, Car sharing is a well-studied transport system, however new developments in technology offer an opportunity for continuing this research. In particular, the study in this thesis is based on two-way CSS where cars are required to be returned to the same base from which they were rented. One way CS, similar to a bike sharing scheme, where cars may be returned to a different station from the collection point is now becoming feasible. The work presented in this thesis should be extended to incorporate one way CSS and the attendant behavioural change of members. The increased flexibility of one-way CS may lead to increased scope of CSS in Ireland and internationally.

In addition, a further study, comparing the estimated impacts derived using the methodology presented in Chapter 4 with the actual impacts of a CSS operating in Dublin would also contribute to the literature in this area. As the CSS operating in Dublin, GoCar, has undergone an expansion in the last 12 months, such a study may be possible in the near future.

8.5.2 Ride Sharing

Of the six models considered, two emerge as suitable candidates for future research. These are the Social Match Algorithm and the Goodwill Models.

The social matching algorithm considers the impact of personal preference on the ability to identify suitable matches; however there is a lack of real data on those who participate in intra-household ride sharing. For instance, while the POWSCAR data (CSO, 2012a) provides excellent data on those who travel as passengers to work, it does not provide any information on those with whom they share their journey. There is a need for both revealed preference and stated preference studies in this area to identify how social preference may impact on the ability to establish successful ride sharing services.

The goodwill models suffer from a similar lack of real data. A better understanding of individual motivation to participate in a RSS and the factors which would contribute to a successful re-registration is required to enable more accurate models of an operational ride sharing service to be designed.

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APPENDIX A: SURVEY QUESTIONS

Thank you for participating!

As part of a Trinity College Dublin research project into Irish travel patterns, we are surveying people on their travel over the last two weeks. This is the Irish version of the survey, if you're based elsewhere, please take the international version.

This survey will take about fifteen minutes to complete and asks questions about your transport patterns, costs and sense of wellbeing.

This survey is all about you. It's about how you get where you need to go and what that costs you. That means you can exclude any travel you do for business (other than your regular journey to work, school or college)

- The first section covers your travel on public transport, walking and cycling
- The second section covers your travel in private cars and other private vehicles
- The third section covers some personal and quality of life details

All answers will be treated in the strictest confidence.

~ Niamh

nrabbitt@tcd.ie

There are 89 questions in this survey

Trains, Buses, Cycling and Walking

1 [PubTranInt]

The first part of the survey asks about your use of different types of transport in the last 2 weeks.

You will be asked whether you used the Train, Buses, Walking, Cycling, Taxis and Rental Cars. If you didn't use the relevant form of transport, the section will be skipped.

If you used more than one mode of transport on a single journey, then you can include each mode in the relevant section.

e.g. if you take a bus and walk, include your bus journey in the bus section and the walking journey in the walking section.

People who complete the survey before the 15th March 2012 will be entered into a prize draw for:

1st Prize: *€250 one4all shopping voucher.*

2nd Prize:*€100 one4all shopping voucher.*

Other prizes: Members of GoCar are also eligible two win two GoCar vouchers of €100 and €50.

2 [Miles or Kilometres]

Would you prefer to answer in miles or kilometres?

Please choose **only one** of the following:

- ○ Miles
- ○ Kilometres

3 [Begin]

It may help to open Google Maps to roughly calculate distances for the survey.

Let's Begin!

Only answer this question if the following conditions are met:
° Answer was A1'Miles' or 'Kilometres' at question '2 [Miles or Kilometres]' (Would you prefer to answer in miles or kilometres?) *and* Answer was A2'Miles' or 'Kilometres' at question '2 [Miles or Kilometres]' (Would you prefer to answer in miles or kilometres?)

Trains

4 [Train Travel]

In the last two weeks, have you travelled by Train in Ireland?

Train includes journeys by Luas, DART, Intercity Rail and Arrow services.

Please choose **only one** of the following:

- ○ Yes
- ○ No

Include only personal journeys and journeys to and from work, school or college.

Exclude business trips.

Include only journeys in Ireland, in the last two weeks.

5 [Train Jour]

In the last two weeks, please tell us:

Only answer this question if the following conditions are met:
° Answer was A1 'Yes' at question '4 [Train Travel]' (In the last two weeks, have you travelled by Train in Ireland? Train includes journeys by Luas, DART, Intercity Rail and Arrow services.)

Please write your answer(s) here:

How many journeys you made by train	
How many minutes in total you spent on the train	
How far in total you travelled by train ({INSERTANS:86411X355X4166})	

A journey is one direction only, so a journey to work and home is two journeys.

Include only your travel by train.

Train includes journeys by Luas, DART, Intercity Rail and Arrow services.

Buses

6 [Bus Travel]

In the last two weeks, have you travelled by Bus in Ireland?

Bus includes journeys on Dublin Bus, Bus Éireann, CityLink Coaches etc.

Please choose **only one** of the following:

- ○ Yes
- ○ No

Include only personal journeys and journeys to and from work, school or college.

Exclude business trips.

Include only journeys in Ireland, in the last two weeks.

7 [Bus Jour]

In the last two weeks, please tell us:

Only answer this question if the following conditions are met:
° Answer was A1'Yes' at question '6 [Bus Travel]' (In the last two weeks, have you travelled by Bus in Ireland? Bus includes journeys on Dublin Bus, Bus Éireann, CityLink Coaches etc.)

Please write your answer(s) here:

How many journeys you made by bus	
How many minutes in total you spent on the bus	
How far in total you travelled by bus ({INSERTANS:86411X355X4166})	

A journey is one direction only, so a journey to work and home is two journeys.

Include only your travel by bus.

Bus includes journeys on Dublin Bus, Bus Éireann, City Link Coaches etc.

Train and Bus Cost

8 [Ticket cost]

How did you pay for <u>these</u> bus and train journeys?

Tick all that apply.

Only answer this question if the following conditions are met:
°

-------- Scenario 1 --------

Answer was A1'Yes' at question '4 [Train Travel]' (In the last two weeks, have you travelled by Train in Ireland? Train includes journeys by Luas, DART, Intercity Rail and Arrow services.)

-------- or Scenario 2 --------

Answer was A1'Yes' at question '6 [Bus Travel]' (In the last two weeks, have you travelled by Bus in Ireland? Bus includes journeys on Dublin Bus, Bus Éireann, CityLink Coaches etc.)

Please choose **all** that apply:

- ☐ Free Travel Pass
- ☐ Annual Ticket(s)
- ☐ Annual Ticket(s) Tax Saver
- ☐ Monthly Ticket(s)
- ☐ 30 Day Ticket(s)
- ☐ Weekly Ticket(s)
- ☐ 10 Journey Ticket(s)
- ☐ 5 Day and 3 Day Ticket(s)
- ☐ 1 Day Ticket(s)
- ☐ Single and Return Ticket(s)
- ☐ Smart Card, Leap Card, Cash Fares

Include only tickets used for personal journeys and journeys to and from work, school or college.

Exclude business trips.

Include only tickets bought in Ireland.

9 [Ticket cost 2]

Do you currently have a:

Only answer this question if the following conditions are met:
° Answer was A2'No' at question '4 [Train Travel]' (In the last two weeks, have you travelled by Train in Ireland? Train includes journeys by Luas, DART, Intercity Rail and Arrow services.) *and* Answer was A2'No' at question '6 [Bus Travel]' (In the last two weeks, have you travelled by Bus in Ireland? Bus includes journeys on Dublin Bus, Bus Éireann, CityLink Coaches etc.)

Please choose **all** that apply:

- ☐ Free Public Transport Pass
- ☐ Annual Ticket for Bus/Luas/Train
- ☐ Annual Tax Saver Ticket for Bus/Luas/Train
- ☐ Monthly Ticket for Bus/Luas/Train
- ☐ 30 Day Ticket for Bus/Luas/Train
- ☐ None of these

10 [Time based]

Give the full price of the annual and monthly tickets in the appropriate box:

Only answer this question if the following conditions are met:
°

-------- Scenario 1 --------

Answer was 2'Annual Ticket(s)' or 'Annual Ticket(s) Tax Saver' or 'Monthly Ticket(s)' or '30 Day Ticket(s)' at question '8 [Ticket cost]' (How did you pay for these bus and train journeys? Tick all that apply.) *and* Answer was 3'Annual Ticket(s)' or 'Annual Ticket(s) Tax Saver' or 'Monthly Ticket(s)' or '30 Day Ticket(s)' at question '8 [Ticket cost]' (How did you pay for these bus and train journeys? Tick all that apply.) *and* Answer was 4'Annual Ticket(s)' or 'Annual Ticket(s) Tax Saver' or 'Monthly Ticket(s)' or '30 Day Ticket(s)' at question '8 [Ticket cost]' (How did you pay for these bus and train journeys? Tick all that apply.) *and* Answer was 5'Annual Ticket(s)' or 'Annual Ticket(s) Tax Saver' or 'Monthly Ticket(s)' or '30 Day Ticket(s)' at question '8 [Ticket cost]' (How did you pay for these bus and train journeys? Tick all that apply.)

-------- or Scenario 2 --------

Answer was SQ001'Monthly Ticket for Bus/Luas/Train' or 'Annual Tax Saver Ticket for Bus/Luas/Train' or 'Annual Ticket for Bus/Luas/Train' or '30 Day Ticket for Bus/Luas/Train' at question '9 [Ticket cost 2]' (Do you currently have a:) *and* Answer was SQ002'Monthly Ticket for Bus/Luas/Train' or 'Annual Tax Saver Ticket for Bus/Luas/Train' or 'Annual Ticket for Bus/Luas/Train' or '30 Day Ticket for Bus/Luas/Train' at question '9 [Ticket cost 2]' (Do you currently have a:) *and* Answer was SQ003'Monthly Ticket for Bus/Luas/Train' or 'Annual Tax Saver Ticket for Bus/Luas/Train' or 'Annual Ticket for Bus/Luas/Train' or '30 Day Ticket for Bus/Luas/Train' at question '9 [Ticket cost 2]' (Do you currently have a:) *and* Answer was SQ005'Monthly Ticket for Bus/Luas/Train' or 'Annual Tax Saver Ticket for Bus/Luas/Train' or 'Annual Ticket for Bus/Luas/Train' or '30 Day Ticket for Bus/Luas/Train' at question '9 [Ticket cost 2]' (Do you currently have a:)

Please write your answer(s) here:

Annual Ticket(s)	
Annual Tax Saver Ticket(s)	
Monthly Ticket(s)	
30 Day Ticket(s)	

Include the cost of all annual or monthly tickets for either bus or train, in the appropriate box.

Give the full cost of the ticket.

11 [Weeklyticket]

In the last two weeks, how much did you spend on 7 Day tickets?

Only answer this question if the following conditions are met:
° Answer was Y at question '8 [Ticket cost]' (How did you pay for these bus and train journeys? Tick all that apply.)

Please write your answer here:

Include only tickets used for personal journeys and journeys to and from work, school or college.

Include only tickets bought in Ireland, in the last two weeks.

12 [10journey]

What is the cost of one 10 journey ticket?

In the last two weeks, how many journeys did you use a ten journey ticket for?

Only answer this question if the following conditions are met:
° Answer was Y at question '8 [Ticket cost]' (How did you pay for these bus and train journeys? Tick all that apply.)

Please write your answer(s) here:

How much is a ten journey ticket? [ ]

In the last two weeks, how many journeys did you use? [ ]

Include only tickets used for personal journeys and journeys to and from work, school or college.

Exclude business trips.

Include only tickets bought in Ireland, in the last two weeks.

13 [DailySinglesRet]

In the last two weeks, how much did you spend on other travel tickets?

e.g. five day tickets, three day tickets, one day tickets, single tickets, return tickets, cash fares, smart card fares

Only answer this question if the following conditions are met:
° Answer was 10'Smart Card, Leap Card, Cash Fares' or 'Single and Return Ticket(s)' or '1 Day Ticket(s)' or '5 Day and 3 Day Ticket(s)' at question '8 [Ticket cost]' (How did you pay for these bus and train journeys? Tick all that apply.) *and* Answer was 7'Smart Card, Leap Card, Cash Fares' or 'Single and Return Ticket(s)' or '1 Day Ticket(s)' or '5 Day and 3 Day Ticket(s)' at question '8 [Ticket cost]' (How did you pay for these bus and train journeys? Tick all that apply.) *and* Answer was 8'Smart Card, Leap Card, Cash Fares' or 'Single and Return Ticket(s)' or '1 Day Ticket(s)' or '5 Day and 3 Day Ticket(s)' at question '8 [Ticket cost]' (How did you pay for these bus and train journeys? Tick all that apply.) *and* Answer was 9'Smart Card, Leap Card, Cash Fares' or 'Single and Return Ticket(s)' or '1 Day Ticket(s)' or '5 Day and 3 Day Ticket(s)' at question '8 [Ticket cost]' (How did you pay for these bus and train journeys? Tick all that apply.)

Please write your answer here:

[ ]

Include only tickets used for personal journeys and journeys to and from work, school or college.

Exclude business trips.

Include only tickets bought in Ireland, in the last two weeks.

Cycling

14 [Cycle Travel]

In the last two weeks, have you travelled by Bicycle in Ireland?

Bicycle travel includes only journeys taken for transport. Cycling for fitness is excluded.

Please choose **only one** of the following:

- ○ Yes
- ○ No

Include only personal journeys and journeys to and from work, school or college.

Exclude business trips.

Include only journeys in Ireland, in the last two weeks.

Include only journeys for transport; cycling for fitness is excluded.

15 [CyclJour]

In the last two weeks, please tell us:

Include only journeys taken for transport. Cycling for fitness is excluded.

Only answer this question if the following conditions are met:
° Answer was A1'Yes' at question '14 [Cycle Travel]' (In the last two weeks, have you travelled by Bicycle in Ireland? Bicycle travel includes only journeys taken for transport. Cycling for fitness is excluded.)

Please write your answer(s) here:

How many journeys in total you made by bicycle	
How many of these journeys used Dublin Bikes	
How many minutes in total you spent cycling for travel	
How far in total you travelled by bicycle ({INSERTANS:86411X355X4166})	

A journey is one direction only, so a journey to work and home is two journeys.

Include only your travel by bicycle.

16 [Dublin Bikes]

When did you register with Dublin Bikes?

Only answer this question if the following conditions are met:
° Answer was A1'Yes' at question '14 [Cycle Travel]' (In the last two weeks, have you travelled by Bicycle in Ireland? Bicycle travel includes only journeys taken for transport. Cycling for fitness is excluded.) *and* Answer was greater than 0 at question '15 [CyclJour]' (In the last two weeks, please tell us: Include only journeys taken for transport. Cycling for fitness is excluded. (How many of these journeys used Dublin Bikes))

Please write your answer(s) here:

Month (mm)	
Year (yy)	

Walking

17 [Foot Travel]

In the last two weeks, have you travelled on Foot in Ireland?

Walking travel includes only journeys taken for transport. Walking for fitness is excluded. Running can be included here, if for instance you run to work.

Please choose **only one** of the following:

- ○ Yes
- ○ No

Include only personal journeys and journeys to and from work, school or college.

Exclude business trips.

Include only journeys in Ireland, in the last two weeks.

Include only journeys for transport; walking for fitness excluded.

18 [WalkJour]

In the last two weeks, please tell us:

Include only journeys taken for transport. Walking for fitness is excluded.

Only answer this question if the following conditions are met:
° Answer was A1'Yes' at question '17 [Foot Travel]' (In the last two weeks, have you travelled on Foot in Ireland? Walking travel includes only journeys taken for transport. Walking for fitness is excluded. Running can be included here, if for instance you run to work.)

Please write your answer(s) here:

How many journeys you made on foot	
How many minutes in total you spent travelling on foot	
How far in total you travelled on foot ({INSERTANS:86411X355X4166})	

A journey is one direction only, so a journey to work and home is two journeys.

Include only your travel on foot.

Taxi

19 [Taxi Travel]

In the last two weeks, have you travelled by Taxi in Ireland?

Taxi travel includes only journeys taken for personal reasons and journeys to and from work, school or college. Business trips are excluded.

Please choose **only one** of the following:

- ○ Yes
- ○ No

Include only personal journeys and journeys to and from work, school or college.

Exclude business trips.

Include only journeys in Ireland, in the last two weeks.

20 [TaxiJour]

In the last two weeks, please tell us:

Only answer this question if the following conditions are met:
° Answer was A1'Yes' at question '19 [Taxi Travel]' (In the last two weeks, have you travelled by Taxi in Ireland? Taxi travel includes only journeys taken for personal reasons and journeys to and from work, school or college. Business trips are excluded.)

Please write your answer(s) here:

How many journeys you made by taxi	
How many minutes in total you spent travelling by taxi	
How far in total you travelled by taxi ({INSERTANS:86411X355X4166})	

A journey is one direction only, so a journey to work and home is two journeys.

Include only your travel by taxi.

21 [Taxicost]

In the last two weeks how much have you spent on taxis?

Include only costs which you cannot claim back from another source.

Only answer this question if the following conditions are met:
° Answer was A1'Yes' at question '19 [Taxi Travel]' (In the last two weeks, have you travelled by Taxi in Ireland? Taxi travel includes only journeys taken for personal reasons and journeys to and from work, school or college. Business trips are excluded.)

Please write your answer here:

Include only costs which you cannot claim back from another source.

Electric Vehicles

22 [EV1]

Have you ever driven an Electric Vehicle?

Please choose **only one** of the following:

- ○ Yes
- ○ No

23 [Benefits]

What do you think are the benefits of Electric Vehicles?

Only answer this question if the following conditions are met:
° Answer was A1'Yes' or 'No' at question '22 [EV1]' (Have you ever driven an Electric Vehicle?) *and* Answer was A2'Yes' or 'No' at question '22 [EV1]' (Have you ever driven an Electric Vehicle?)

Please write your answer here:

24 [Drawbacks]

What do you think are the drawbacks of Electric Vehicles?

Only answer this question if the following conditions are met:
° Answer was A1'No' or 'Yes' at question '22 [EV1]' (Have you ever driven an Electric Vehicle?) *and* Answer was A2'No' or 'Yes' at question '22 [EV1]' (Have you ever driven an Electric Vehicle?)

Please write your answer here:

GoCar

25 [GC1]

Are you a member of GoCar?

Please choose **only one** of the following:

- ○ Yes
- ○ No
- ○ I don't know what GoCar is

This includes only journeys taken for transport personal reasons. Business trips are excluded.

26 [DatJoin]

When did you register with GoCar?

Only answer this question if the following conditions are met:
° Answer was 1'Yes' at question '25 [GC1]' (Are you a member of GoCar?)

Please write your answer(s) here:

Month (mm) ☐

Year (yy) ☐

27 [Tariff]

Which GoCar tariff have you chosen?

Only answer this question if the following conditions are met:
° Answer was 1'Yes' at question '25 [GC1]' (Are you a member of GoCar?)

Please choose **only one** of the following:

- ○ Pre-April 2011 Tariff
- ○ Occasional (€5 monthly fee)
- ○ Regular (€10 monthly fee)
- ○ Active (€15 monthly fee)

28 [GoCarjour]

In the last two weeks, please tell us:

This question is about your journeys in GoCar, not GoCar bookings. You may have made several journeys in a single booking.

Only answer this question if the following conditions are met:
° Answer was 1'Yes' at question '25 [GC1]' (Are you a member of GoCar?)

Please write your answer(s) here:

How many journeys you made by GoCar	
How many minutes in total you spent travelling in a GoCar	
How far in total you travelled by by GoCar ({INSERTANS:86411X355X4166})	

A journey is one direction only, so a journey to work and home is two journeys.

Include only personal journeys and journeys to work, school or college.

Exclude business trips.

Include only journeys in Ireland, in the last two weeks.

29 [Passengers]

Was it usually just you in the GoCar?

Only answer this question if the following conditions are met:
° Answer was 1'Yes' at question '25 [GC1]' (Are you a member of GoCar?) *and* Answer was greater than 0 at question '28 [GoCarjour]' (In the last two weeks, please tell us: This question is about your journeys in GoCar, not GoCar bookings. You may have made several journeys in a single booking. (How many journeys you made by GoCar))

Please choose **only one** of the following:

- ○ Just Me
- ○ Myself and one other person
- ○ Myself and two other people
- ○ Myself and three other people
- ○ Myself and four other people
- ○ More than that

Choose whichever was most often.

30 [GoCarcost]

Except for your monthly tariff, in the last two weeks, how much have you spent on GoCar?

Include only costs which you cannot claim back from another source.

Only answer this question if the following conditions are met:
° Answer was 1'Yes' at question '25 [GC1]' (Are you a member of GoCar?) *and* Answer was greater than or equal to 0 at question '28 [GoCarjour]' (In the last two weeks, please tell us: This question is about your journeys in GoCar, not GoCar bookings. You may have made several journeys in a single booking. (How many journeys you made by GoCar))

Please write your answer here:

If the amount was split between several people, please include only your costs.

Include only costs which you cannot claim back from another source.

Vehicles - Cost

31 [CarCostInt]

The next section of the survey covers your travel in private vehicles, e.g. cars, vans and motorcycles.

Since most vehicle costs are paid yearly, the first part will ask about your spending on vehicles in the last year.

This is about how much <u>you</u> spent on insurance, motor tax etc. over the last year.
This could be for your own car or for a car owned by a partner, friend or relative.

32 [Contributed?]Except for fuel, have you contributed to the cost of a vehicle in the last 12 months?

Please choose **only one** of the following:

- ○ Yes to vehicle(s) I owned
- ○ Yes to vehicle(s) owned by someone else
- ○ Yes to several different vehicles owned by myself and others
- ○ No

33 [Vehicle Costs]

Except for fuel, in the last 12 months I have paid the following costs:

For regular payments you can give the weekly, monthy or annual amount.

Only answer this question if the following conditions are met:
° Answer was 1'Yes to vehicle(s) owned by someone else' or 'Yes to several different vehicles owned by myself and others' or 'Yes to vehicle(s) I owned' at question '32 [Contributed?]' (Except for fuel, have you contributed to the cost of a vehicle in the last 12 months?) *and* Answer was 2'Yes to vehicle(s) owned by someone else' or 'Yes to several different vehicles owned by myself and others' or 'Yes to vehicle(s) I owned' at question '32 [Contributed?]' (Except for fuel, have you contributed to the cost of a vehicle in the last 12 months?) *and* Answer was 3'Yes to vehicle(s) owned by someone else' or 'Yes to several different vehicles owned by myself and others' or 'Yes to vehicle(s) I owned' at question '32 [Contributed?]' (Except for fuel, have you contributed to the cost of a vehicle in the last 12 months?)

Please write your answer(s) here:

Purchase Payments	
Regular Payment Amount on Loan or HP	
Motor Tax	
Insurance (for yourself only)	
Maintenance and NCT	
Other expenses (tolls, parking, fines, roadside assistance)	

Purchase payments includes any value you received for the trade in of another vehicle.

If you spent money on modifications to the vehicle, please include this under other.

34 [RegPaym]

The regular payment amount given is the:

Only answer this question if the following conditions are met:
° Answer was greater than 0 at question '33 [Vehicle Costs]' (Except for fuel, in the last 12 months I have paid the following costs: For regular payments you can give the weekly, monthy or annual amount. (Regular Payment Amount on Loan or HP))

Please choose **only one** of the following:

- ○ Total paid in the last 12 months
- ○ Monthly payment made for the last 12 months
- ○ Weekly payment made for the last 12 months

35 [Depreciation]

How much have the vehicles you own depreciated in the last 12 months?

Only answer this question if the following conditions are met:
° Answer was 1'Yes to several different vehicles owned by myself and others' or 'Yes to vehicle(s) I owned' at question '32 [Contributed?]' (Except for fuel, have you contributed to the cost of a vehicle in the last 12 months?) *and* Answer was 3'Yes to several different vehicles owned by myself and others' or 'Yes to vehicle(s) I owned' at question '32 [Contributed?]' (Except for fuel, have you contributed to the cost of a vehicle in the last 12 months?)

Please write your answer here:

[ ]

36 [SoldVeh]

Have you traded in or sold a vehicle in the last 12 months?

Only answer this question if the following conditions are met:
° Answer was 1'Yes to several different vehicles owned by myself and others' or 'Yes to vehicle(s) I owned' at question '32 [Contributed?]' (Except for fuel, have you contributed to the cost of a vehicle in the last 12 months?) *and* Answer was 3'Yes to several different vehicles owned by myself and others' or 'Yes to vehicle(s) I owned' at question '32 [Contributed?]' (Except for fuel, have you contributed to the cost of a vehicle in the last 12 months?)

Please choose **only one** of the following:

- ○ Yes
- ○ No

37 [SalePrice]

How much did you receive?

Only answer this question if the following conditions are met:
° Answer was A1'Yes' at question '36 [SoldVeh]' (Have you traded in or sold a vehicle in the last 12 months?) *and* Answer was 1'Yes to several different vehicles owned by myself and others' or 'Yes to vehicle(s) I owned' at question '32 [Contributed?]' (Except for fuel, have you contributed to the cost of a vehicle in the last 12 months?) *and* Answer was 3'Yes to several different vehicles owned by myself and others' or 'Yes to vehicle(s) I owned' at question '32 [Contributed?]' (Except for fuel, have you contributed to the cost of a vehicle in the last 12 months?)

Please write your answer here:

[ ]

Please enter the amount you received whether as a cash value or as a trade in payment.

Private Travel, Vehicle 1

38 [PTIntGC]

In the next part of the survey we want to find out about your travel in private vehicles.

Exclude your GoCar travel from your answers in this section.

Only answer this question if the following conditions are met:
° Answer was 1'Yes' at question '25 [GC1]' (Are you a member of GoCar?)

39 [PTInt]

In the next part of the survey we want to find out about your travel in private vehicles.

Only answer this question if the following conditions are met:
° Answer was 'I don't know what GoCar is' or 'No' at question '25 [GC1]' (Are you a member of GoCar?) *and* Answer was 2'I don't know what GoCar is' or 'No' at question '25 [GC1]' (Are you a member of GoCar?) *and* Answer was 3'I don't know what GoCar is' or 'No' at question '25 [GC1]' (Are you a member of GoCar?)

40 [PTTravel]

In the last two weeks have you travelled in a private vehicle?

E.g. privately owned cars, motorcycles and vans.

Include only journeys taken for personal journeys and journeys to work, school or college.

Please choose **only one** of the following:

- ○ Yes one vehicle
- ○ Yes two vehicles
- ○ Yes more than two vehicles
- ○ I own a vehicle but have not travelled in any private vehicle for longer than two weeks
- ○ No

Include cars, motorcycles and vans.

Include only personal journeys and journeys to work, school or college.

Exclude business trips.

Include only journeys in Ireland, in the last two weeks.

Include rental cars other than GoCar.

41 [PTMost]

In this part of the survey we want to find out about the vehicle you travelled the furthest distance in, in the last 2 weeks so we can calculate your carbon footprint.

Only answer this question if the following conditions are met:
° Answer was A2'Yes more than two vehicles' or 'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A3'Yes more than two vehicles' or 'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

42 [PTOwn]

Do you own this vehicle?

Only answer this question if the following conditions are met:
° Answer was A1'Yes one vehicle' or 'Yes two vehicles' or 'Yes more than two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A2'Yes one vehicle' or 'Yes two vehicles' or 'Yes more than two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A3'Yes one vehicle' or 'Yes two vehicles' or 'Yes more than two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please choose **only one** of the following:

- ○ Yes
- ○ No

43 [PTVehType]

What type of vehicle is it?

Only answer this question if the following conditions are met:
° Answer was A1'I own a vehicle but have not travelled in any private vehicle for longer than two weeks' or 'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A2'I own a vehicle but have not travelled in any private vehicle for longer than two weeks' or 'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A3'I own a vehicle but have not travelled in any private vehicle for longer than two weeks' or 'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A4'I own a vehicle but have not travelled in any private vehicle for longer than two weeks' or 'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please choose **only one** of the following:

- ○ Car
- ○ Motorcycle
- ○ Van
- ○ Other [ ]

44 [PTCarYear]

In what year was the car manufactured?

Only answer this question if the following conditions are met:
° Answer was A1'Car' at question '43 [PTVehType]' (What type of vehicle is it?)

Please choose **only one** of the following:

- ○ Pre1995
- ○ 1995
- ○ 1996
- ○ 1997
- ○ 1998
- ○ 1999
- ○ 2000
- ○ 2001
- ○ 2002
- ○ 2003
- ○ 2004
- ○ 2005
- ○ 2006
- ○ 2007
- ○ 2008 Before July 1st
- ○ 2008 After July 1st
- ○ 2009
- ○ 2010
- ○ 2011
- ○ 2012
- ○ Don't know

45 [2c]

What is the cars engine size?

Only answer this question if the following conditions are met:
° Answer was 1'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 10'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 11'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 12'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 13'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 14'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 15'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 2'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 3'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 4'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 5'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 6'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 7'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 8'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 9'1996' or '2007' or '2008 Before July 1st' or '1998' or '1997' or '2006' or '2002' or '2001' or '1999' or '2000' or '2005' or '2003' or '2004' or '1995' or 'Pre1995' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was A1'Car' at question '43 [PTVehType]' (What type of vehicle is it?)

Please choose **only one** of the following:

- ○ 0 - 1000cc
- ○ 1001 - 1100cc
- ○ 1101 - 1200cc
- ○ 1201 - 1300cc
- ○ 1301 - 1400cc
- ○ 1401 - 1500cc
- ○ 1501 - 1600cc
- ○ 1601 - 1700cc
- ○ 1701 - 1800cc
- ○ 1801 - 1900cc
- ○ 1901 - 2000cc
- ○ 2001 - 2100cc
- ○ 2101 - 2200cc
- ○ 2201 - 2300cc
- ○ 2301 - 2400cc
- ○ 2401 - 2500cc
- ○ 2501 - 2600cc
- ○ 2601 - 2700cc
- ○ 2701 - 2800cc
- ○ 2801 - 2900cc
- ○ 2901 - 3000cc
- ○ 3001 - 15000cc
- ○ I don't know

46 [2d]

What is the cars motor tax band?

To help you choose the correct band, the 2011 and 2012 motor tax rates and bands are given in the table:

Tax Band	Annual Motor Tax	
gCO_2/km	2011	2012
0-120	€104	€160
121-140	€156	€225
141-155	€302	€330
156-170	€447	€481
171-190	€630	€677
191-225	€1,050	€1,129
226-999	€2,100	€2,258

Only answer this question if the following conditions are met:
° Answer was 16'2012' or '2011' or '2010' or '2009' or '2008 After July 1st' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 17'2012' or '2011' or '2010' or '2009' or '2008 After July 1st' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 18'2012' or '2011' or '2010' or '2009' or '2008 After July 1st' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 19'2012' or '2011' or '2010' or '2009' or '2008 After July 1st' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 20'2012' or '2011' or '2010' or '2009' or '2008 After July 1st' at question '44 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was A1'Car' at question '43 [PTVehType]' (What type of vehicle is it?)

Please choose **only one** of the following:

- ○ 0 - 120 gCO_2/km
- ○ 121 - 140 gCO_2/km
- ○ 141 - 155 gCO_2/km
- ○ 156 - 170 gCO_2/km
- ○ 171 - 190 gCO_2/km
- ○ 191 - 225 gCO_2/km
- ○ 226 - 999 gCO_2/km
- ○ Don't know

47 [PTCMYear]

In what year was the vehicle manufactured?

Only answer this question if the following conditions are met:
° Answer was -oth-'Motorcycle' or 'Van' at question '43 [PTVehType]' (What type of vehicle is it?) *and* Answer was A2'Motorcycle' or 'Van' at question '43 [PTVehType]' (What type of vehicle is it?) *and* Answer was A3'Motorcycle' or 'Van' at question '43 [PTVehType]' (What type of vehicle is it?)

Please choose **only one** of the following:

- ○ Pre 1995
- ○ 1995
- ○ 1996
- ○ 1997
- ○ 1998
- ○ 1999
- ○ 2000
- ○ 2001
- ○ 2002
- ○ 2003
- ○ 2004
- ○ 2005
- ○ 2006
- ○ 2007
- ○ 2008
- ○ 2009
- ○ 2010
- ○ 2011
- ○ 2012
- ○ Don't Know

48 [MCCO2]

Which tax band is your motorcycle?

To help you choose the correct band, these are the 2011 motortax rates for motorcycles:

Engine Size	*Annual Cost (2011)*
0-75cc	**€43**
76-200cc	**€58**
201-9999cc	**€76**

Only answer this question if the following conditions are met:
° Answer was A2'Motorcycle' at question '43 [PTVehType]' (What type of vehicle is it?)

Please choose **only one** of the following:

- ○ 0-75cc
- ○ 76-200cc
- ○ 201-9999cc
- ○ Don't know

49 [VanEngineSize]

What is the engine size?

Only answer this question if the following conditions are met:
° Answer was -oth-'Van' at question '43 [PTVehType]' (What type of vehicle is it?) *and* Answer was A3'Van' at question '43 [PTVehType]' (What type of vehicle is it?)

Please write your answer here:

50 [VDMTrav]

In the last two weeks, please tell us:

Only answer this question if the following conditions are met:
° Answer was A1'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A2'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A3'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please write your answer(s) here:

How many journeys you made in this vehicle as the driver	
How many journeys you made in this vehicle as a passenger	
How many minutes in total you spent in this vehicle	
How far in total you travelled in this vehicle ({INSERTANS:86411X355X4166})	

A journey is one direction only, so a journey to work and home is two journeys.

Include only personal journeys and journeys to work, school or college.

Exclude business trips.

Include only journeys in Ireland, in the last two weeks.

51 [VDMpass]

On average how many people accompanied you in this vehicle?

Only answer this question if the following conditions are met:
° Answer was A1'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A2'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A3'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please choose **only one** of the following:

- ○ Just me
- ○ One passenger and driver
- ○ Two passengers and driver
- ○ Three passengers and driver
- ○ Four passengers and driver
- ○ More than four passengers and driver

52 [Fuel Cost]

In the last two weeks, how much have you spent in total on fuel for this vehicle?

Since business mileage includes a payment for wear and tear, and a payment for fuel, please put the total cost of fuel for all your trips here and enter any costs you can claim back in the next question.

Only answer this question if the following conditions are met:
° Answer was A1'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A2'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A3'Yes two vehicles' or 'Yes more than two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please write your answer here:

Include only journeys in Ireland, in the last two weeks.

53 [Expenses]

How much can you claim back for travel in this vehicle, in the last two weeks?

Include only this vehicle.

Only answer this question if the following conditions are met:
° Answer was A1'Yes more than two vehicles' or 'Yes two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A2'Yes more than two vehicles' or 'Yes two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A3'Yes more than two vehicles' or 'Yes two vehicles' or 'Yes one vehicle' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please write your answer here:

Include only journeys in Ireland, in the last two weeks.

Private Travel, Vehicle 2

54 [Blank]

This page is blank as the question group doesn't apply to you.

Please click next.

Only answer this question if the following conditions are met:
° Answer was 'No' or 'I own a vehicle but have not travelled in any private vehicle for longer than two weeks' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A4'No' or 'I own a vehicle but have not travelled in any private vehicle for longer than two weeks' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A5'No' or 'I own a vehicle but have not travelled in any private vehicle for longer than two weeks' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

55 [PT3+veh]

In the next part of the survey we want to find out about your travel in the other private vehicles you travelled in over the last two weeks.

Please answer these questions for all the other private vehicles you travelled in.

Only answer this question if the following conditions are met:
° Answer was A3'Yes more than two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

56 [PTInt]

In the next part of the survey we want to find out about your travel in the other private vehicle you travelled in over the last two weeks.

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

57 [PTOwn]

Do you own this vehicle?

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please choose **only one** of the following:

- ○ Yes
- ○ No

58 [PTVehType]

What type of vehicle is it?

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please choose **only one** of the following:

- ○ Car
- ○ Motorcycle
- ○ Van
- ○ Other [ ]

59 [PTCarYear]

In what year was the car manufactured?

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A1'Car' at question '58 [PTVehType]' (What type of vehicle is it?)

Please choose **only one** of the following:

- ○ Pre1995
- ○ 1995
- ○ 1996
- ○ 1997
- ○ 1998
- ○ 1999
- ○ 2000
- ○ 2001
- ○ 2002
- ○ 2003
- ○ 2004
- ○ 2005
- ○ 2006
- ○ 2007
- ○ 2008 Before July 1st
- ○ 2008 After July 1st
- ○ 2009
- ○ 2010
- ○ 2011
- ○ 2012
- ○ Don't know

60 [2c]

What is the cars engine size?

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A1'Car' at question '58 [PTVehType]' (What type of vehicle is it?) *and* Answer was 1'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 10'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 11'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 12'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 13'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 14'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 15'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 2'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 3'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 4'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 5'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 6'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 7'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 8'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 9'2001' or '1999' or '2000' or '2002' or '1997' or '2006' or '1998' or '2004' or '1995' or 'Pre1995' or '2003' or '2005' or '1996' or '2007' or '2008 Before July 1st' at question '59 [PTCarYear]' (In what year was the car manufactured?)

Please choose **only one** of the following:

- ○ 0 - 1000cc
- ○ 1001 - 1100cc
- ○ 1101 - 1200cc
- ○ 1201 - 1300cc
- ○ 1301 - 1400cc
- ○ 1401 - 1500cc
- ○ 1501 - 1600cc
- ○ 1601 - 1700cc
- ○ 1701 - 1800cc
- ○ 1801 - 1900cc
- ○ 1901 - 2000cc
- ○ 2001 - 2100cc
- ○ 2101 - 2200cc
- ○ 2201 - 2300cc
- ○ 2301 - 2400cc
- ○ 2401 - 2500cc
- ○ 2501 - 2600cc
- ○ 2601 - 2700cc
- ○ 2701 - 2800cc
- ○ 2801 - 2900cc
- ○ 2901 - 3000cc
- ○ 3001 - 15000cc
- ○ I don't know

61 [2d]

What is the cars motor tax band?

To help you choose the correct band, the 2011 and 2012 motor tax rates and bands are given in the table:

Tax Band	Annual Motor Tax	
gCO_2/km	2011	2012
0-120	€104	€160
121-140	€156	€225
141-155	€302	€330
156-170	€447	€481
171-190	€630	€677
191-225	€1,050	€1,129
226-999	€2,100	€2,258

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A1'Car' at question '58 [PTVehType]' (What type of vehicle is it?) *and* Answer was 16'2011' or '2010' or '2012' or '2008 After July 1st' or '2009' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 17'2011' or '2010' or '2012' or '2008 After July 1st' or '2009' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 18'2011' or '2010' or '2012' or '2008 After July 1st' or '2009' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 19'2011' or '2010' or '2012' or '2008 After July 1st' or '2009' at question '59 [PTCarYear]' (In what year was the car manufactured?) *and* Answer was 20'2011' or '2010' or '2012' or '2008 After July 1st' or '2009' at question '59 [PTCarYear]' (In what year was the car manufactured?)

Please choose **only one** of the following:

- ○ 0 - 120 gCO_2/km
- ○ 121 - 140 gCO_2/km
- ○ 141 - 155 gCO_2/km
- ○ 156 - 170 gCO_2/km
- ○ 171 - 190 gCO_2/km
- ○ 191 - 225 gCO_2/km
- ○ 226 - 999 gCO_2/km
- ○ Don't know

62 [PTCMYear]

In what year was the vehicle manufactured?

Only answer this question if the following conditions are met:
° Answer was -oth-'Motorcycle' or 'Van' at question '58 [PTVehType]' (What type of vehicle is it?) *and* Answer was A2'Motorcycle' or 'Van' at question '58 [PTVehType]' (What type of vehicle is it?) *and* Answer was A3'Motorcycle' or 'Van' at question '58 [PTVehType]' (What type of vehicle is it?)

Please choose **only one** of the following:

- ○ Pre 1995
- ○ 1995
- ○ 1996
- ○ 1997
- ○ 1998
- ○ 1999
- ○ 2000
- ○ 2001
- ○ 2002
- ○ 2003
- ○ 2004
- ○ 2005
- ○ 2006
- ○ 2007
- ○ 2008
- ○ 2009
- ○ 2010
- ○ 2011
- ○ 2012
- ○ Don't Know

63 [MCCO2]

Which tax band is your motorcycle?

To help you choose the correct band, these are the 2011 motortax rates for motorcycles:

Engine Size	*Annual Cost (2011)*
0-75cc	**€43**
76-200cc	**€58**
201-9999cc	**€76**

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was A2'Motorcycle' at question '58 [PTVehType]' (What type of vehicle is it?)

Please choose **only one** of the following:

- ○ 0-75cc
- ○ 76-200cc
- ○ 201-9999cc
- ○ Don't know

64 [VanEngineSize]

What is the engine size?

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.) *and* Answer was -oth-'Van' at question '58 [PTVehType]' (What type of vehicle is it?) *and* Answer was A3'Van' at question '58 [PTVehType]' (What type of vehicle is it?)

Please write your answer here:

65 [VDM1veh]

In the last two weeks, please tell us:

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please write your answer(s) here:

How many journeys you made in this vehicle as the driver	
How many journeys you made in this vehicle as a passenger	
How many minutes in total you spent in this vehicle	
How far in total you travelled in this vehicle ({INSERTANS:86411X355X4166})	

A journey is one direction only, so a journey to work and home is two journeys.

Include only personal journeys and journeys to work, school or college.

Exclude business trips.

Include only journeys in Ireland, in the last two weeks.

66 [VDM Vehicles]

In the last two weeks, please tell us:

Only answer this question if the following conditions are met:
° Answer was A3'Yes more than two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please write your answer(s) here:

How many journeys you made in these vehicles as the driver	
How many journeys you made in these vehicles as a passenger	
How many minutes in total you spent in these vehicles	
How far in total you travelled in these vehicles ({INSERTANS:86411X355X4166})	

A journey is one direction only, so a journey to work and home is two journeys.

Include only personal journeys and journeys to work, school or college.

Exclude business trips.

Include only journeys in Ireland, in the last two weeks.

67 [VDMpass]

On average how many people accompanied you in this vehicle?

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please choose **only one** of the following:

- ◯ Just me
- ◯ One passenger and driver
- ◯ Two passengers and driver
- ◯ Three passengers and driver
- ◯ Four passengers and driver
- ◯ More than four passengers and driver

68 [VDMPass2]

On average how many people accompanied you in these vehicles?

Only answer this question if the following conditions are met:
° Answer was A3'Yes more than two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please choose **only one** of the following:

- ◯ Just me
- ◯ One passenger and driver
- ◯ Two passengers and driver
- ◯ Three passengers and driver
- ◯ Four passengers and driver
- ◯ More than four passengers and driver

69 [Fuel Cost]

In the last two weeks, how much have you spent in total on fuel for this vehicle?

Since business mileage includes a payment for wear and tear, and a payment for fuel, please put the total cost of fuel for all your trips here and enter any costs you can claim back in the next question.

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please write your answer here:

Include only journeys in Ireland, in the last two weeks.

70 [Fuel Cost Vehicles]

In the last two weeks, how much have you spent in total on fuel for these vehicles?

Since business mileage includes a payment for wear and tear, and a payment for fuel, please put the total cost of fuel for all your trips here and enter any costs you can claim back in the next question.

Only answer this question if the following conditions are met:
° Answer was A3'Yes more than two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please write your answer here:

Include only journeys in Ireland, in the last two weeks.

71 [Expenses]

How much can you claim back for travel in this vehicle, in the last two weeks?

Include only this vehicle.

Only answer this question if the following conditions are met:
° Answer was A2'Yes two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please write your answer here:

Include only journeys in Ireland, in the last two weeks.

72 [Expenses Vehicles]

How much can you claim back for travel in these vehicles, in the last two weeks?

Include all other vehicles.

Only answer this question if the following conditions are met:
° Answer was A3'Yes more than two vehicles' at question '40 [PTTravel]' (In the last two weeks have you travelled in a private vehicle? E.g. privately owned cars, motorcycles and vans. Include only journeys taken for personal journeys and journeys to work, school or college.)

Please write your answer here:

Include only journeys in Ireland, in the last two weeks.

Social Health and Wellbeing Questions

73 [113a]

This study is also looking at the social side of travel patterns and sustainability.

Peoples travel patterns are affected by their health and their well-being.

Peoples travel patterns may also affect their health and well-being.

To help us examine the social side of sustainability, please answer these questions:

74 [115]

Please indicate for each of the five statements which is closest to how you have been feeling over the last two weeks.

Please choose the appropriate response for each item:

	All of the time	Most of the time	More than half of the time	Less than half of the time	Some of the time	At no time
1) I have felt cheerful and in good spirits	○	○	○	○	○	○
2) I have felt calm and relaxed	○	○	○	○	○	○
3) I have felt active and vigorous	○	○	○	○	○	○
4) I woke up feeling fresh and rested	○	○	○	○	○	○
5) My daily life has been filled with things that interest me	○	○	○	○	○	○

75 [114]

Other than the cycling and walking you've already listed, how many minutes have you spent in the last two weeks doing:

Exclude any physical activity (i.e. walking, cycling) you have previously included.

Please write your answer(s) here:

Intense Physical Activity	
Moderate Physical Activity	

76 [113b]

How is your health in general?

Please choose **only one** of the following:

- ○ Very Good
- ○ Good
- ○ Fair
- ○ Bad
- ○ Very Bad

Personal Details

77 [PQFinal]

This is the final section of the survey.

The questions are some personal details which will help us to compare your travel to that of other people and to data available from other sources such as the central statistics office.

78 [Age]

What age categories do you and other members of your household belong to?

Please choose the appropriate response for each item:

	0-18	19-23	24-30	31-35	36-40	41-45	46-50	51-55	56-60	61-65	66-74	75 and older
You	○	○	○	○	○	○	○	○	○	○	○	○
Person 2	○	○	○	○	○	○	○	○	○	○	○	○
Person 3	○	○	○	○	○	○	○	○	○	○	○	○
Person 4	○	○	○	○	○	○	○	○	○	○	○	○
Person 5	○	○	○	○	○	○	○	○	○	○	○	○
Person 6	○	○	○	○	○	○	○	○	○	○	○	○

Fill in as many as apply.

79 [Sex]

Are you male or female?

Please choose **only one** of the following:

○ Female

○ Male

80 [Living]

Where do you live?

Anywhere within 200m of your home is fine.

Right click to place the pin.

Please write your answer here:

81 [Working?]

How would you describe your present principal status?

Please choose **only one** of the following:

- ○ Working for payment or profit
- ○ Looking for first regular job
- ○ Unemployed
- ○ Student or pupil
- ○ Looking after home/family
- ○ Retired from employment
- ○ Unable to work due to permanent sickness or disability
- ○ Other [ ]

82 [Work]

Realistically what ways could you use to travel to your place of work or education?

Consider your health, availability of parking, bus timetables, the time you need to arrive and depart, how long it would take etc.

If it would take too long, it's not realistic.

Only answer this question if the following conditions are met:
° Answer was -oth-'Working for payment or profit' or 'Student or pupil' at question '81 [Working?]' (How would you describe your present principal status?) *and* Answer was 1'Working for payment or profit' or 'Student or pupil' at question '81 [Working?]' (How would you describe your present principal status?) *and* Answer was 4'Working for payment or profit' or 'Student or pupil' at question '81 [Working?]' (How would you describe your present principal status?)

Please choose **all** that apply:

- ☐ Train
- ☐ Bus
- ☐ Cycling
- ☐ Walking
- ☐ Car

Choose all that apply.

83 [Typical?]

Have the last two weeks been typical of your normal travel patterns in the last year?

Please choose **only one** of the following:

- ○ Yes
- ○ No

84 [Explain]

Please Explain:

Only answer this question if the following conditions are met:
° Answer was N'No' at question '83 [Typical?]' (Have the last two weeks been typical of your normal travel patterns in the last year?)

Please write your answer here:

Conclusion

85 [119a]

Thank you for completing this survey!

Your answers will help us better understand how and why people travel, and whether or not changes can reduce carbon emissions, improve well being and offer economic benefits.

Do you have any comments to make on the survey?

Please write your answer here:

86 [Email]

If you wish to enter the competition for the €250 and €100 All For One Voucher, or the GoCar competition please enter your email address.

The winner will be selected after the 15th of March 2012.

Please write your answer here:

87 [Further contact]

It would really help our research if you were willing to particpate in further surveys.

Are you willing to help us further with any of these?

We will use the email address you have provided to contact you only for those you agree to here. If you do not select any, we will only contact you again if you win the competition.

Please choose **all** that apply:

- ☐ I would be willing to answer this questionnaire again in one year
- ☐ I would be willing to participate in other surveys and interviews

88 [Email no comp]

Your answer suggests you're willing to participate in further research, but don't wish to partipate in the competition.

Please give your contact details below.

Only answer this question if the following conditions are met:
°

-------- Scenario 2 --------

Answer was at question '86 [Email]' (If you wish to enter the competition for the €250 and €100 All For One Voucher, or the GoCar competition please enter your email address. The winner will be selected after the 15th of March 2012.) *and* Answer was Y at question '87 [Further contact]' (It would really help our research if you were willing to particpate in further surveys. Are you willing to help us further with any of these? We will use the email address you have provided to contact you only for those you agree to here. If you do not select any, we will only contact you again if you win the competition.)

-------- or Scenario 3 --------

Answer was at question '86 [Email]' (If you wish to enter the competition for the €250 and €100 All For One Voucher, or the GoCar competition please enter your email address. The winner will be selected after the 15th of March 2012.) *and* Answer was Y at question '87 [Further contact]' (It would really help our research if you were willing to particpate in further surveys. Are you willing to help us further with any of these? We will use the email address you have provided to contact you only for those you agree to here. If you do not select any, we will only contact you again if you win the competition.)

Please write your answer here:

89 [Friends]

We need as many people as possible to answer this survey.

Please share the survey on facebook and twitter:

Tweet 4

Or email and shout from this link from the rooftops: www.survey.researchthecity.com

If you're interested in the project's results, they will be available here over the next few months. Nothing personal will be shown. Individual answers won't be identifiable.

Some quick and simplistic results from the pilot survey can already be seen here.

Thank you and goodbye!

01.01.1970 – 01:00

Submit your survey.
Thank you for completing this survey.

APPENDIX B: PROGRAMMING CODE

```
library(rgdal)
library(rms)
library(gmodels)
library(sp)

rm(list=ls(all=TRUE))

setwd("C:/Documents and Settings/nrabbitt/My Documents/Dropbox/Ridematching Paper")
setwd("C:/Users/nrabbitt/Dropbox/Ridematching Paper")


#########################
##Read in Full Data Set##
#########################

##Read in the Powcar Data of Dublin Residents

powcar<-read.table("powcardublin.txt",header=TRUE,sep="\t")

powcar$X<-NULL

#Give everyone an ID number
powcar$CommuterNumber<-1:nrow(powcar)

############################
##Clean up data set in Phases
############################

##only live and work within Dublin then remove
powcar<-powcar[powcar$POWSC_NUTS3=="IE021",]
powcar<-powcar[powcar$Residence_NUTS3=="IE021",]

##Remove other location details
powcar$POWSC_NUTS3<-NULL
powcar$powsc_location<-NULL
powcar$Residence_NUTS3<-NULL
powcar$Residence_County<-NULL
powcar$powsc_county<-NULL
powcar$Residence_CSOED<-NULL
powcar$Residence_OSIED<-NULL
powcar$POWSC_CSOED<-NULL
powcar$POWSC_OSiED<-NULL
powcar$Residence_Town<-NULL
powcar$POWSC_Town<-NULL
powcar$POWSC_Area_Type<-NULL
powcar$Residence_Area_Type<-NULL
powcar$Resident_Persons<-NULL
powcar$Resident_Workers<-NULL
powcar$Resident_Students<-NULL
powcar$Nature_of_Occupancy<-NULL
powcar$Year_Built<-NULL
powcar$One_off_house_indicator<-NULL
powcar$Cars_or_vans<-NULL
powcar$Marital_Status<-NULL
powcar$Household_Composition<-NULL
powcar$Family_unemployed_parents<-NULL
powcar$Highest_Level_Ed_Parents<-NULL
powcar$Nationality_Student<-NULL
powcar$Religion_Student<-NULL
powcar$Able_to_speak_English_Student<-NULL

powcar<-powcar[powcar$School_level!="1",]
powcar<-powcar[powcar$School_level!="2",]
powcar$School_level<-NULL

powcar$Usual_Residence_One_Year_Ago<-NULL
powcar$Highest_Level_of_Education<-NULL
powcar$Industrial_Group<-NULL

##Take out those who don't state a means of travel
##Remove those who don't work, and work from home,

powcar$Means_of_Travel<-as.character(powcar$Means_of_Travel)
powcar<-powcar[powcar$Means_of_Travel!="*",]
```

```
powcar<-powcar[powcar$Means_of_Travel!="11",]
powcar<-powcar[powcar$Means_of_Travel!="01",]
powcar$Means_of_Travel<-as.factor(powcar$Means_of_Travel)

#Paste an A to Small Area names
powcar$Residence_Small_Area<-paste0("A",powcar$Residence_Small_Area)
powcar$POWSC_Small_area<-paste0("A",powcar$POWSC_Small_area)


##Make NS times of departure out and factor
powcar$Time_of_Departure<-as.character(powcar$Time_of_Departure)
powcar<-powcar[powcar$Time_of_Departure!="*",]
powcar<-powcar[powcar$Time_of_Departure!="1",]
powcar$Time_of_Departure<-as.factor(powcar$Time_of_Departure)

##Make Journey minutes into a Numeric variable
powcar<-powcar[powcar$Journey_Minutes!="-",]
powcar$Journey_Minutes<-as.numeric(as.character(powcar$Journey_Minutes))


##Remove final superflous columns
powcar$WSC_Ind<-NULL
powcar$School_level<-NULL


##Process Age and SEG variables into correct levels and assign numeric values

powcar<-powcar[powcar$Five_Year_Age_Group!="-",]
powcar$Five_Year_Age_Group<-as.character(powcar$Five_Year_Age_Group)
powcar$Five_Year_Age_Group<-factor(powcar$Five_Year_Age_Group,
levels=c("15-19","20-24","25-29","30-34","35-39","40-44","45-49","50-54",
"55-59","60-64","65-69","70-74","75+"))
powcar$Five_Year_Age_Group<-as.numeric(powcar$Five_Year_Age_Group)

powcar$SEG<-as.character(powcar$SEG)
powcar[powcar$SEG=="H",c("SEG")]<-"C"
powcar[powcar$SEG=="I",c("SEG")]<-"C"
powcar[powcar$SEG=="J",c("SEG")]<-"F"
powcar[powcar$SEG=="Z",c("SEG")]<-"C"

powcar$SEG<-factor(powcar$SEG,
levels=c("A","B","C","D","E","F","G"))
powcar$SEG<-as.numeric(powcar$SEG)

powcar$Sex<-as.numeric(powcar$Sex)


########################################

#Make sure Residence is as character
powcar$Residence_Small_Area<-as.character(powcar$Residence_Small_Area)

#Remove Work Location (using Eastings and Northings)
powcar$POWSC_Small_area<-NULL

#################################
###### Create Randomised Origin Points within Each SA as home location

New.Home<-0
a<-1

if (New.Home==1){
set.seed(a)


SmallAreas<-readOGR("C:/Documents and Settings/nrabbitt/My Documents/Dropbox
/Ridematching Paper/All Small Areas/Census2011_Small_Areas_generalised20m.shp",
layer="Census2011_Small_Areas_generalised20m",input_field_name_encoding="utf8")
SmallAreas<-SmallAreas[SmallAreas$NUTS3=="IE021",]


ted<-seq(15000,nrow(powcar),by=15000)
ted[length(ted)+1]<-nrow(powcar)
j<-1
```

```
for (t in ted){

Homes<-powcar[j:t,c("CommuterNumber","Residence_Small_Area")]
j<-t+1
Homes$RHomeX<-0
Homes$RHomeY<-0

for (i in 1:nrow(Homes)){

Homes$RHomeX[i]<-spsample(SmallAreas[SmallAreas@data$GEOGID==Homes$Residence_Small_Area[i],],
n=1,type="random",iter=100)@coords[1]

Homes$RHomeY[i]<-spsample(SmallAreas[SmallAreas@data$GEOGID==Homes$Residence_Small_Area[i],],
n=1,type="random",iter=100)@coords[2]
}
outfile<-paste0(t,"Homes",a,".txt")
write.table(Homes,outfile,sep="\t")
rm(Homes)
print(t)
}

Homes<-matrix(data=0,nrow=0,ncol=4)
Homes<-as.data.frame(Homes)
colnames(Homes)<-c("CommuterNumber","Residence_Small_Area","RHomeX","RHomeY")


for (t in ted){
infile<-paste0(t,"Homes",a,".txt")
Homes.1<-read.table(infile,header=TRUE,sep="\t")
Homes<-rbind(Homes,Homes.1)
}
outfile<-paste0("Homes",a,".txt")
write.table(Homes,outfile,sep="\t")
rm(Homes.1,SmallAreas,ted)
}

##For Normal runs, just read in an appropriate set of home locations

if (New.Home!=1) {
infile<-paste0("Homes",a,".txt")
Homes<-read.table(infile,header=TRUE,sep="\t")
}

Homes$Residence_Small_Area<-NULL
powcar$Residence_Small_Area<-NULL

powcar<-merge(powcar,Homes,by="CommuterNumber",all.x=TRUE,sort=FALSE)
Homes<-NULL

powcar.store<-powcar


#################
##Drivers Only

powcar<-powcar[powcar$Means_of_Travel=="07",]

powcar$Means_of_Travel<-NULL

###########################################
##Create Start Time and Arrival Time Numbers
a<-1
set.seed(a)

powcar$Time_of_Departure<-as.character(powcar$Time_of_Departure)

#FIRST USE SIX CENTRAL POINTS
z<-as.data.frame(table(powcar$Time_of_Departure))
z<-z[2:(nrow(z)-1),]

y<-matrix(data=0,nrow=6,ncol=2)
y<-as.data.frame(y)
colnames(y)<-c("X","Y")
```

```
rownames(y)<-1:6

y$Y[1:6]<-z$Freq/30
y$X[1:6]<-seq(405,555,30)

X<-matrix(data=0,nrow=0,ncol=2)
X<-as.data.frame(X)
colnames(X)<-c("X","Y")


for (i in 1:(nrow(y)-1)){
RATE<-(y$Y[i+1]-y$Y[i])/(y$X[i+1]-y$X[i])
x<-as.data.frame(y$X[i]:y$X[i+1])
colnames(x)[1]<-"X"
x$Y<-0
x$Y[1]<-y$Y[i]
for (j in 2:nrow(x)){x$Y[j]<-x$Y[j-1]+RATE}
x<-x[-nrow(x),]
X<-rbind(X,x)
}

rm(x)

X[nrow(X)+1,]<-y[nrow(y),]

LHT<-sum(X$Y[1:15])
RHT<-sum(X$Y[nrow(X):(nrow(X)-15)])

z<-as.data.frame(table(powcar$Time_of_Departure))

LHT<-z$Freq[2]-LHT+z$Freq[1]
RHT<-z$Freq[nrow(z)-1]-RHT+z$Freq[nrow(z)]

MAX.L<-X$Y[1]
MAX.R<-X$Y[nrow(X)]


z<-as.data.frame(table(powcar$Time_of_Departure))

i<-0.001
TEST<-0
while(round(TEST,4)<round(X$Y[1],4)){
i<-i+0.000001
EXP.L<-dexp(X$X[1]:1,rate=i)
EXP.L<-EXP.L*(LHT/sum(EXP.L))
TEST<-max(EXP.L)
}

j<-0.0001
TEST<-0
while(round(TEST,4)<round(X$Y[nrow(X)],4)){
j<-j+0.000001
EXP.R<-dexp(X$X[nrow(X)]:1440,rate=j)
EXP.R<-EXP.R*(RHT/sum(EXP.R))
TEST<-max(EXP.R)
}

EXP.L<-as.data.frame(EXP.L)
EXP.L$X<-1:X$X[1]
colnames(EXP.L)[1]<-"Y"
EXP.L<-EXP.L[,c("X","Y")]

EXP.R<-as.data.frame(EXP.R)
EXP.R$X<-X$X[nrow(X)]:1440
colnames(EXP.R)[1]<-"Y"
EXP.R<-EXP.R[,c("X","Y")]

X<-X[-nrow(X),]
X<-X[-1,]

X<-rbind(EXP.L,X,EXP.R)

plot(X$X,X$Y)
```

```
y<-X$Y

#Assign Numbers

powcar$ArrivalTime<-NULL
powcar$StartTime<-NULL
powcar$StartTime<-NA


powcar[powcar$Time_of_Departure=="2",ncol(powcar)]<-
sample(1:390,nrow(powcar[powcar$Time_of_Departure=="2",]),replace=TRUE,prob=y[1:390])

powcar[powcar$Time_of_Departure=="3",ncol(powcar)]<-
sample(391:420,nrow(powcar[powcar$Time_of_Departure=="3",]),replace=TRUE,prob=y[391:420])

powcar[powcar$Time_of_Departure=="4",ncol(powcar)]<-
sample(421:450,nrow(powcar[powcar$Time_of_Departure=="4",]),replace=TRUE,prob=y[421:450])

powcar[powcar$Time_of_Departure=="5",ncol(powcar)]<-
sample(451:480,nrow(powcar[powcar$Time_of_Departure=="5",]),replace=TRUE,prob=y[451:480])

powcar[powcar$Time_of_Departure=="6",ncol(powcar)]<-
sample(481:510,nrow(powcar[powcar$Time_of_Departure=="6",]),replace=TRUE,prob=y[481:510])

powcar[powcar$Time_of_Departure=="7",ncol(powcar)]<-
sample(511:540,nrow(powcar[powcar$Time_of_Departure=="7",]),replace=TRUE,prob=y[511:540])

powcar[powcar$Time_of_Departure=="8",ncol(powcar)]<-
sample(541:570,nrow(powcar[powcar$Time_of_Departure=="8",]),replace=TRUE,prob=y[541:570])

powcar[powcar$Time_of_Departure=="9",ncol(powcar)]<-
sample(571:1440,nrow(powcar[powcar$Time_of_Departure=="9",]),replace=TRUE,prob=y[571:1440])

powcar$ArrivalTime<-powcar$StartTime+powcar$Journey_Minutes

lemon<-0
if (lemon==1){
jpeg("Results/HistogramofDepartureTimeBands.jpeg")
hist(as.numeric(powcar$Time_of_Departure),xlab="Departure Bands, 2-before 6:30,
3-6.31-7am ...9-after 9.30",col="gray75",main="Histogram of Departure Bands")

dev.off()

jpeg("Results/HistogramofStarttime.jpeg")
hist(powcar$StartTime,breaks=1440,xlab="Start Time, 480=8am",
xlim=c(0,1440),ylim=c(0,1500),main="Histogram of Start Time",col="gray75")
abline(v=480,col="red",lty=2)
dev.off()

jpeg("Results/HistogramofArrivaltime.jpeg")
hist(powcar$ArrivalTime,breaks=1440,xlab="Arrival Time, 540=9am",
xlim=c(0,1440),ylim=c(0,2000),main="Histogram of Arrival Time",col="gray75")
abline(v=540,col="red",lty=2)
dev.off()
}

powcar$Time_of_Departure<-NULL
powcar$Journey_Minutes<-NULL
powcar$StartTime<-NULL

#################################
###### Add random number to Eastings and Northings

powcar$Fuzz_East_250<-as.numeric(as.character(powcar$Fuzz_East_250))
powcar$Fuzz_North_250<-as.numeric(as.character(powcar$Fuzz_North_250))

powcar$RWorkX<-sample(-125:125,nrow(powcar),replace=TRUE)
powcar$RWorkY<-sample(-125:125,nrow(powcar),replace=TRUE)

powcar$RWorkX<-powcar$RWorkX+powcar$Fuzz_East_250
powcar$RWorkY<-powcar$RWorkY+powcar$Fuzz_North_250

powcar$Fuzz_East_250<-NULL
powcar$Fuzz_North_250<-NULL
```

```
##Calculate Distance
A<-powcar$RHomeX-powcar$RWorkX
A<-A/1000
B<-powcar$RHomeY-powcar$RWorkY
B<-B/1000
A<-A*A
B<-B*B

powcar$Distance<-round(sqrt(A+B),2)

A<-NULL
B<-NULL



############################
##The Goodwill Column is a measure of likeliness of participating

powcar$Goodwill<-1


########################
##store list

powcar.store<-powcar

########################
##Get rid of unneeded variables

rm(a,A,B,Homes,infile,New.Home,y,EXP.R,EXP.L,MAX.L,MAX.R,X,z,i,j,lemon,
TEST,LHT,RATE,RHT)

bob<-0
if(bob==1){
##Output of whole process

Output2<-matrix(data=0,nrow=0,ncol=25)
Output2<-as.data.frame(Output2)
colnames(Output2)<-c("D0","D1","D2","D3","P0","P1","Total","StartDrivers",
"BatchSize","Flexibles","DriversOnly","NumBatches","NumDays","AddPassengers","ClusterSize",
"DriverSeats","TimeGap","DistHome","DistWork","DistTotal","SocialChance","No.Match",
"Yes.Match","TotalDistance","P1Distance")

outfile<-paste0("Results/Case3ResultsB.txt")

write.table(Output2,outfile,append=TRUE,sep="\t",col.names=TRUE)
}
rm(bob)

CHARACTERISTICS<-matrix(data=0,nrow=3,ncol=5)
CHARACTERISTICS<-as.data.frame(CHARACTERISTICS)
colnames(CHARACTERISTICS)<-c("gazebo","DistHome","DistWork","TotalDist","TimeGap")
CHARACTERISTICS[1,]<-c(10,0.75,0.75,1.25,15)
CHARACTERISTICS[2,]<-c(5,2,2,3,20)
CHARACTERISTICS[3,]<-c(2,3,3,5,30)



#Case 3

#case3<-read.table("Case3Finalizing.txt",header=TRUE,sep="\t")

#for (CAS in 65:1){

#Initial.Drivers<-case3$Initial.Drivers[CAS]
#Number.Batches<-case3$NumBatches[CAS]
#Retention.Rate<-case3$AddPassengers[CAS]

for (Retention.Rate in c(0,0.5)){
for (Initial.Drivers in seq(0.1,1,0.1)){
for (Number.Batches in seq(1,10,1)){
```

```
#Case 2
C2<-matrix(data=c(0.1,1,0.5,0.5,1,0),nrow=3,ncol=2,byrow=TRUE)

#for (Drivers.Passengers in c(0.1)){
#for (FLEX in c(1)){

for (alphabet in c(2)){
Drivers.Passengers<-C2[alphabet,1]
FLEX<-C2[alphabet,2]


#Case 1

#for(gazebo in c(5)){
for (ralph in c(2)){
gazebo<-CHARACTERISTICS$gazebo[ralph]

#######################################
##Start the Iterations
#######################################

set.seed(sample(1:14201,1))

powcar<-powcar.store

########################
##Set Some Parmeters##
######################

#Calculate Total Number of Registrants
ALL<-round(nrow(powcar)*gazebo/100,0)

#Calculate Total Number of Drivers (Initial + Bj in all batches)
TotDrivers<-round(ALL*Drivers.Passengers/(1+Drivers.Passengers),0)


##Number of Drivers in Original Pool
Drivers.PR<-round(TotDrivers*Initial.Drivers,0)

##Calculate Number of People Who Register Later
TotPassengers<-ALL-Drivers.PR


##Batch Size (i.e. all the drivers, mixed and passengers in a batch)
NPassengers<-round(TotPassengers/Number.Batches,0)

#Number of Drivers only in a batch
#(Note these are included in NPassengers the Batch Size too)
NDrivers<-round((TotDrivers-Drivers.PR)/Number.Batches,0)

##Number of Passengers in a batch who are also Drivers
NMixed<-round((NPassengers-NDrivers)*FLEX,0)



##Number of Batches/Day
NBatches<-Number.Batches

#Number of Days
NDays<-3

#Add what Proportion of unmatched passengers to the next batch?
#0 - 1

AddPassengers<-Retention.Rate

##Cluster Size
NumberperCluster<-10

##Maximum Number of Passengers
Passengers<-3

##Journey Parameters
Minutes<-CHARACTERISTICS$TimeGap[ralph]
```

```
DistanceHome<-CHARACTERISTICS$DistHome[ralph]
DistanceWork<-CHARACTERISTICS$DistWork[ralph]
TotalWalk<-CHARACTERISTICS$TotalDist[ralph]

#Match Chance
#ie for every degree of difference in Sex/Age and Social Class,
#the chances of a match are multiplied by Chance (Set to 1 to exclude Social Matching)
Chance<-1

##Match in What Order (Distance,HomeD,WorkD,ATGap, EuclideanDist, or Position (in batch)

Match.Order<-"EuclideanDist"

##Goodwill

#Starting Goodwill
Goodwill<-100

#Changes with matches
NoMatch<-(-0.5)
Yes.Match<-1

#####################################
##Output Variables

Batch.Match<-matrix(data=0,nrow=0,ncol=9)
colnames(Batch.Match)<-c("Distance","HomeD","WorkD","ATGap","EuclideanDist","Passengers",
"DriverNumber","PassengerNumber","Position")

Record<-matrix(data=0,nrow=0,ncol=2)
Record<-as.data.frame(Record)
colnames(Record)<-c("CommuterNumber","Match")

Output<-matrix(data=0,nrow=nrow(powcar),ncol=2)
Output<-as.data.frame(Output)
colnames(Output)<-c("CommuterNumber","Day")
Output$CommuterNumber<-powcar$CommuterNumber

powcar$Goodwill<-Goodwill

#################
##START DAY ONE##
#################

for (d in 1:NDays){

########################################
##GET THE POOL OF DRIVERS AND PASSENGERS##
########################################

#mix up powcar
powcar<-powcar[sample(nrow(powcar),nrow(powcar),replace=FALSE),]
powcar.1<-powcar[powcar$Goodwill<=0,]
powcar<-powcar[powcar$Goodwill>0,]
powcar<-rbind(powcar,powcar.1)
rm(powcar.1)

#Drivers are the first rows, everyone else gets assigned to the population,

Drivers<-powcar[1:Drivers.PR,]
Population<-powcar[(Drivers.PR+1):nrow(powcar),]


#####################################################################
##Cluster drivers on home location, work location and arrival time

k<-round(nrow(Drivers)/NumberperCluster,0)


Drivers.scale<-scale(Drivers[,c("ArrivalTime","RHomeX","RHomeY","RWorkX","RWorkY")])
Scale.Centre<-attributes(Drivers.scale)$`scaled:center`
Scale.Scale<-attributes(Drivers.scale)$`scaled:scale`

fit <- kmeans(Drivers.scale[,c("ArrivalTime","RHomeX","RHomeY","RWorkX","RWorkY")],
```

```
k,iter.max=100)

Clusters<-aggregate(Drivers.scale,by=list(fit$cluster),FUN=mean)
colnames(Drivers.scale)<-paste0("Scaled.",colnames(Drivers.scale))
Drivers<- data.frame(Drivers,Drivers.scale, fit$cluster)
colnames(Drivers)[ncol(Drivers)]<-"Cluster"
Drivers.scale<-NULL

Drivers$Passengers<-0

rm(k,Drivers.scale,fit)

Old.Drivers<-Drivers[0,]

################################################
##Phase 2 - Match Multiple Batches of Passengers##
################################################

#Create empty dataframe - batch.store, which later stores left over passengers

Batch.store<-matrix(data=0,nrow=0,ncol=12)
Batch.store<-as.data.frame(Batch.store)
colnames(Batch.store)<-c("CommuterNumber","Sex","Five_Year_Age_Group",
"SEG","RHomeX","RHomeY","RWorkX","RWorkY","ArrivalTime","Distance",
"Goodwill","Role")

#Create a left overs variable
Leftovers<-Batch.store

#Start Number of batches goes here

for (N in 1:NBatches){

##Choose The First Batch

Batch<-Population[(((NPassengers)*(N-1))+1):(NPassengers*N),]

##Assign to be Passenger or Mixed
Batch$Role<-"P"

if (NMixed>0){
Batch$Role[0:NMixed]<-"M"
}

if (NDrivers>0){
Batch$Role[nrow(Batch):(nrow(Batch)-NDrivers+1)]<-"D"
}

##Reorder batch so that Mixed aren't all at the start
##(This is now the "order they arrive in"
Batch<-Batch[sample(nrow(Batch),nrow(Batch),replace=FALSE),]


#If Passengers from old batches are added to new batches
if(AddPassengers>0){

#Get the correct proportion of lines from Batch.store (only if Batch.store has something in it)

if (nrow(Batch.store)>0){

#randomly reorder Batch.store
Batch.store<-Batch.store[sample(nrow(Batch.store),nrow(Batch.store),replace=FALSE),]

#Get the Leftovers

Leftovers.1<-Batch.store[(round(AddPassengers*nrow(Batch.store),0)+1):nrow(Batch.store),]
Leftovers<-rbind(Leftovers,Leftovers.1)


#number of lines we want from Batch.store
Batch.store<-Batch.store[1:(round(AddPassengers*nrow(Batch.store),0)),]
Batch<-rbind(Batch.store,Batch)
```

```
}
}


##Assign Closest Cluster to all Batch

#Scale Batch
Batch.Scale<-Batch[,c("ArrivalTime","RHomeX","RHomeY","RWorkX","RWorkY")]
rownames(Batch.Scale)<-Batch$CommuterNumber

for(j in 1:ncol(Batch.Scale)){
Batch.Scale[,j]<-(Batch.Scale[,j]-Scale.Centre[j])/Scale.Scale[j]}

Batch$Cluster<-0

#Calculate Euclidean Distance for each person
for (b in 1:nrow(Batch.Scale)){

Clusters$EuclideanDist<-
sqrt((Clusters$ArrivalTime-Batch.Scale$ArrivalTime[b])^2+
(Clusters$RHomeX-Batch.Scale$RHomeX[b])^2+
(Clusters$RHomeY-Batch.Scale$RHomeY[b])^2+
(Clusters$RWorkX-Batch.Scale$RWorkX[b])^2+
(Clusters$RWorkY-Batch.Scale$RWorkY[b])^2)

Clusters<-Clusters[order(Clusters$EuclideanDist),]

Batch$Cluster[b]<-Clusters$Group.1[1]
Batch$EucDist[b]<-Clusters$EuclideanDist[1]
}

#Tidy up the Batch Variable
colnames(Batch.Scale)<-paste0("Scaled.",colnames(Batch.Scale))
Batch<-data.frame(Batch,Batch.Scale)
Batch$Position<-1:nrow(Batch)

rm(Batch.Scale)


#Add mixed role passengers to drivers
if(NMixed>0){
Batch.M<-Batch[Batch$Role=="M",]
Batch.M<-Batch.M[,c(colnames(Drivers)[1:(ncol(Drivers)-1)])]
Batch.M$Passengers<-0
Drivers<-rbind(Drivers,Batch.M)
rm(Batch.M)
}

#Add drivers role passengers to drivers
if (NDrivers>0){
Batch.D<-Batch[Batch$Role=="D",]
Batch.D<-Batch.D[,c(colnames(Drivers)[1:(ncol(Drivers)-1)])]
Batch.D$Passengers<-0
Drivers<-rbind(Drivers,Batch.D)

for (DR in 1:nrow(Batch.D)){
Batch<-Batch[Batch$CommuterNumber!=Batch.D$CommuterNumber[DR],]}

rm(DR,Batch.D)
}


##Create a list of all possible matches in the Batch

for (j in 1:nrow(Batch)){

#for the individual j, take all the drivers in the Cluster
Matches.Ind<-Drivers[Drivers$Cluster==Batch$Cluster[j],]

#Calculate the values for the constraints
Matches.Ind$HomeD<-
sqrt((Matches.Ind$RHomeX-Batch$RHomeX[j])^2+(Matches.Ind$RHomeY-Batch$RHomeY[j])^2)/1000

Matches.Ind$WorkD<-
```

```
sqrt((Matches.Ind$RWorkX-Batch$RWorkX[j])^2+(Matches.Ind$RWorkY-Batch$RWorkY[j])^2)/1000

Matches.Ind$ATGap<-abs(Matches.Ind$ArrivalTime-Batch$ArrivalTime[j])

##Apply Constraints Set 1
Matches.Ind<-Matches.Ind[Matches.Ind$HomeD<=DistanceHome,]
Matches.Ind<-Matches.Ind[Matches.Ind$WorkD<=DistanceWork,]
Matches.Ind<-Matches.Ind[(Matches.Ind$HomeD+Matches.Ind$WorkD)<=TotalWalk,]
Matches.Ind<-Matches.Ind[Matches.Ind$ATGap<=Minutes,]

#Calculate Social Probability
if(nrow(Matches.Ind)>0){
Matches.Ind$Sex<-1-(abs(Matches.Ind$Sex-Batch$Sex[j])*(1-Chance))
Matches.Ind$Five_Year_Age_Group<-
1-(abs(Matches.Ind$Five_Year_Age_Group-Batch$Five_Year_Age_Group[j])*(1-Chance))

Matches.Ind$SEG<-1-(abs(Matches.Ind$SEG-Batch$SEG[j])*(1-Chance))

Matches.Ind$Chance<-Matches.Ind$Sex*Matches.Ind$Five_Year_Age_Group*Matches.Ind$SEG

for (z in 1:nrow(Matches.Ind)){
Matches.Ind$Chance[z]<-sample(c(1,0),1,prob=c(Matches.Ind$Chance[z],1-Matches.Ind$Chance[z]))}

#Take the Matches that Pass the Social Matching
Matches.Ind<-Matches.Ind[Matches.Ind$Chance==1,]

#Close out the Social Probability Phase
}

#Process the remaining matches:

if(nrow(Matches.Ind)>0){

#Calculate Euclidean Distance for the matches
Matches.Ind$EuclideanDist<-
sqrt((Matches.Ind$Scaled.ArrivalTime-Batch$Scaled.ArrivalTime[j])^2+
(Matches.Ind$Scaled.RHomeX-Batch$Scaled.RHomeX[j])^2+
(Matches.Ind$Scaled.RHomeY-Batch$Scaled.RHomeY[j])^2+
(Matches.Ind$Scaled.RWorkX-Batch$Scaled.RWorkX[j])^2+
(Matches.Ind$Scaled.RWorkY-Batch$Scaled.RWorkY[j])^2)

#Create the variable for storing in the overall list of matches

Matches.Ind<-
Matches.Ind[,c("CommuterNumber","Distance","HomeD","WorkD","ATGap","EuclideanDist","Passengers")]

Matches.Ind$DriverNumber<-Matches.Ind$CommuterNumber
Matches.Ind$PassengerNumber<-Batch$CommuterNumber[j]
Matches.Ind$Position<-j
Matches.Ind$CommuterNumber<-NULL

#Bind the variable to the other matches for this batch
Batch.Match<-rbind(Batch.Match,Matches.Ind)
}
#Finish creating the list of possible matches for the batch
}

rm(Matches.Ind)

#Remove matches where the driver == the passenger
Batch.Match$Spare<-Batch.Match$DriverNumber-Batch.Match$PassengerNumber
Batch.Match<-Batch.Match[Batch.Match$Spare!=0,]
Batch.Match$Spare<-NULL


##Create Column to record passenger matches
Batch$Match<-0


##For all variables, except distance, smallest has priority, therefore invert Distance

Batch.Match$Distance<-max(Batch.Match$Distance)-Batch.Match$Distance

##Order Batch.Match to the ordering variable
```

```
Batch.Match<-Batch.Match[order(Batch.Match[[Match.Order]]),]

###################
##Start Matching Process

while(nrow(Batch.Match)>0){

##Identify Initial List of Passengers who only have one match

Passenger.1<-as.data.frame(table(Batch.Match$PassengerNumber))
Passenger.1<-Passenger.1[Passenger.1$Freq==1,]

#Record Passenger.1 matches in Batch
#Start with the first, remove the passenger from the Driver,Batch and Matches variables
#Check the Driver doesn't have 3 passengers, and if they do remove them from the
#Matches variable then remake Passenger.1 (in case the two removals have affected
#other matches)

while(nrow(Passenger.1)>0){

#Order Passenger.1 in Batch Order

Batch.P<-Batch[,c("CommuterNumber","Position")]
Passenger.1<-merge(Passenger.1,Batch.P,by.x="Var1",by.y="CommuterNumber",all.x=TRUE)
rm(Batch.P)
Passenger.1<-Passenger.1[order(Passenger.1$Position),]
Passenger.1$Position<-NULL

PN<-as.numeric(as.character(Passenger.1[1,1]))

#Record the first row of Passenger.1 having a match in the batch variable

Batch$Match2<-0
Batch[Batch$CommuterNumber==PN,c("Match2")]<-1
Batch$Match2[is.na(Batch$Match2)] <- 0
Batch$Match<-Batch$Match+Batch$Match2

#Record the first row Passenger.1's match in Driver Record

DN<-as.numeric(as.character(Batch.Match[Batch.Match$PassengerNumber==PN,c("DriverNumber")]))
Drivers$Passenger2<-0
Drivers[Drivers$CommuterNumber==DN,c("Passenger2")]<-1
Drivers$Passenger2[is.na(Drivers$Passenger2)] <- 0
Drivers$Passengers<-Drivers$Passengers+Drivers$Passenger2


#Check if the Driver is a Passenger in any of the Matches or in the Batch
#and remove
Batch.Match<-Batch.Match[Batch.Match$PassengerNumber!=DN,]
Batch<-Batch[Batch$CommuterNumber!=DN,]

#Check if the Passenger is a Driver in any of the matches or in the driver list
Drivers<-Drivers[Drivers$CommuterNumber!=PN,]
Batch.Match<-Batch.Match[Batch.Match$DriverNumber!=PN,]

#Check if there are three passengers and remove Driver from BatchMatch if that's the case
if(Drivers$Passengers[which(Drivers$CommuterNumber==DN)]>=Passengers){
Batch.Match<-Batch.Match[Batch.Match$DriverNumber!=DN,]}

#Take out Passenger from Batch.Match
Batch.Match<-Batch.Match[Batch.Match$PassengerNumber!=PN,]

#Just in case Batch.Match is now empty
if (nrow(Batch.Match)>0){
#Remake the Passenger.1 variable
Passenger.1<-as.data.frame(table(Batch.Match$PassengerNumber))
Passenger.1<-Passenger.1[Passenger.1$Freq==1,]
}

if (nrow(Batch.Match)==0){Passenger.1<-Passenger.1[0,]}

#Close out matching passengers with only one match
}
```

```
##Match the passenger with highest priority according to the criteria (Distance etc.)

#Just in case Batch.Match is now empty
if (nrow(Batch.Match)>0){

PN<-as.numeric(as.character(Batch.Match$PassengerNumber[1]))

Batch$Match2<-0
Batch[Batch$CommuterNumber==PN,c("Match2")]<-1
Batch$Match2[is.na(Batch$Match2)] <- 0
Batch$Match<-Batch$Match+Batch$Match2

DN<-as.numeric(as.character(Batch.Match$DriverNumber[1]))
Drivers$Passenger2<-0
Drivers[Drivers$CommuterNumber==DN,c("Passenger2")]<-1
Drivers$Passenger2[is.na(Drivers$Passenger2)] <- 0
Drivers$Passengers<-Drivers$Passengers+Drivers$Passenger2

#Check if the Driver is a Passenger in any of the Matches and
#remove from the match and the batch
Batch.Match<-Batch.Match[Batch.Match$PassengerNumber!=DN,]
Batch<-Batch[Batch$CommuterNumber!=DN,]

#Check if the Passenger is a Driver in any of the matches
#and remove from the match and the Drivers
Batch.Match<-Batch.Match[Batch.Match$DriverNumber!=PN,]
Drivers<-Drivers[Drivers$CommuterNumber!=PN,]

#Check if there are three passengers and remove Driver from BatchMatch if that's the case
if(Drivers$Passengers[which(Drivers$CommuterNumber==DN)]>=Passengers){
Batch.Match<-Batch.Match[Batch.Match$DriverNumber!=DN,]}

#Take out Passenger
Batch.Match<-Batch.Match[Batch.Match$PassengerNumber!=PN,]

#Finish the second part of the matching algorithm (the bit after Passenger.1)
}

#Finish the While Statement (All of Batch.Match has been matched)
}

Batch$Match2<-NULL
Drivers$Passenger2<-NULL

#Take out any Drivers who are full and store them in an "OldDrivers" variable
Old.Drivers.1<-Drivers[Drivers$Passengers>=Passengers,]
Drivers<-Drivers[Drivers$Passengers<Passengers,]
Old.Drivers<-rbind(Old.Drivers,Old.Drivers.1)
rm(Old.Drivers.1)

#Remove unmatched Passengers from the Batch

Batch.store.1<-Batch[Batch$Match==0,]
Batch<-Batch[Batch$Match==1,]

#Since all mixed passengers are already in the drivers pool, make them passengers
Batch.store.1$Role<-"P"

#Fix columns
Batch.store.1<-Batch.store.1[,c(colnames(Batch.store))]

##Adjust Batch.store.1 depending on AddPassengers variable
if (AddPassengers>0){Batch.store<-Batch.store.1}
if (AddPassengers==0){Batch.store<-rbind(Batch.store,Batch.store.1)}


#Finish Processing this batch

##Add the Batch$Match Column back into the Record Column
Record<-rbind(Record,Batch[,c("CommuterNumber","Match")])

#Finish processing the batches
}
```

```
##Add the old Drivers back to the Drivers
Drivers<-rbind(Drivers,Old.Drivers)

#Add unmatched passengers to the record

#Recombine Leftovers and Batch.store
Batch.store<-rbind(Batch.store,Leftovers)

Batch.store$Match<-0
Record<-rbind(Record,Batch.store[,c("CommuterNumber","Match")])

#Store Days results for Drivers and Passengers in a result variable

Output[,d+1]<-0
colnames(Output)[d+1]<-paste0("Day",d)
Record$Match<-paste0("P",Record$Match)
Drivers.Record<-Drivers[,c("CommuterNumber","Passengers")]
colnames(Drivers.Record)<-c("CommuterNumber","Match")
Drivers.Record$Match<-paste0("D",Drivers.Record$Match)
Record<-rbind(Record,Drivers.Record)
Output<-merge(Output,Record,by="CommuterNumber",all.x=TRUE,sort=FALSE)

Output$Match[is.na(Output$Match)] <- "NS"
Output[,(d+1)]<-Output$Match


#Reset Record and Drivers Record
Record<-Record[0,]

#Adjust Goodwill in powcar
powcar<-powcar[order(powcar$CommuterNumber),]

##Get rid of Duplicates in Output, which are created by NMixed not being
##Matched. These are assigned to ????

TEST.1<-as.numeric(duplicated(Output$CommuterNumber),fromLast=FALSE)
TEST.2<-as.numeric(duplicated(Output$CommuterNumber,fromLast=TRUE))
TEST<-TEST.1+TEST.2
rm(TEST.1,TEST.2)

Output$Match2<-as.character(TEST)

Output[Output$Match2=="1",c("Match")]<-"P0"
Output$Match2<-NULL

Output<-Output[!duplicated(Output$CommuterNumber),]

rm(TEST)

##Combine powcar and Match

Output<-Output[order(Output$CommuterNumber),]
powcar$Match<-as.factor(Output$Match)

lev <- with(powcar, levels(Match))
lev[lev == "D0"] <- NoMatch
lev[lev == "P0"] <- NoMatch
lev[lev == "NS"] <- 0
lev[lev == "P1"] <- Yes.Match
lev[lev == "D1"] <- Yes.Match
lev[lev == "D2"] <- Yes.Match
lev[lev == "D3"] <- Yes.Match
powcar <- within(powcar, levels(Match) <- lev)

rm(lev)

powcar$Goodwill<-powcar$Goodwill+as.numeric(as.character(powcar$Match))

Output$Match<-NULL
powcar$Match<-NULL

#Finish out the Day
print(d)
```

```
print(CAS)

}

Success<-matrix(data=c("D0","D1","D2","D3","P0","P1","NS"),ncol=1,nrow=7)
Success<-as.data.frame(Success)
colnames(Success)<-"Var1"

for (i in 2:ncol(Output)){
Success.1<-as.data.frame(table(Output[,i]))
colnames(Success.1)[2]<-colnames(Output)[i]
Success<-merge(Success,Success.1,by="Var1",all.x=TRUE,sort=FALSE)
}

#Replace NA with 0
Success[is.na(Success)]<-0

##Calculate Distances off the Output Variable
Output$Distance<-powcar$Distance

#Calcualte TotalDistance
Output.Total<-Output

ted<-colnames(Output.Total)[2:(ncol(Output.Total)-1)]

for (i in ted){

OT<-as.data.frame(Output.Total[[i]])
OT[,1]<-as.factor(OT[,1])
colnames(OT)<-"BOB"
lev <- with(OT, levels(BOB))
lev[lev == "D0"] <- 1
lev[lev == "P0"] <- 1
lev[lev == "NS"] <- 0
lev[lev == "P1"] <- 1
lev[lev == "D1"] <- 1
lev[lev == "D2"] <- 1
lev[lev == "D3"] <- 1
OT <- within(OT, levels(BOB) <- lev)
Output.Total[[i]]<-as.numeric(as.character(OT[,1]))
Output.Total[[i]]<-Output.Total[[i]]*Output.Total$Distance
}

Output.T<-Output.Total
Output.T<-Output.T[,-1]
Output.T<-Output.T[,-ncol(Output.T)]
Output.T<-colSums(Output.T)


Output.Total<-Output

ted<-colnames(Output.Total)[2:(ncol(Output.Total)-1)]

for (i in ted){

OT<-as.data.frame(Output.Total[[i]])
OT[,1]<-as.factor(OT[,1])
colnames(OT)<-"BOB"
lev <- with(OT, levels(BOB))
lev[lev == "D0"] <- 0
lev[lev == "P0"] <- 0
lev[lev == "NS"] <- 0
lev[lev == "P1"] <- 1
lev[lev == "D1"] <- 0
lev[lev == "D2"] <- 0
lev[lev == "D3"] <- 0
OT <- within(OT, levels(BOB) <- lev)
Output.Total[[i]]<-as.numeric(as.character(OT[,1]))
Output.Total[[i]]<-Output.Total[[i]]*Output.Total$Distance
}

Output.Total<-Output.Total[,-1]
Output.Total<-Output.Total[,-ncol(Output.Total)]
Output.Total<-colSums(Output.Total)
```

```
####################
rownames(Success)<-Success$Var1
Success<-Success[-which(Success$Var1=="NS"),]
Success$Var1<-NULL
Success<-as.data.frame(t(Success))

POD<-seq(.1,10,.1)
POD<-POD[1:nrow(Success)]
rownames(Success)<-paste0(as.numeric(Sys.time())+POD)

Success<-Success[,c("D0","D1","D2","D3","P0","P1")]

Success$Total<-rowSums(Success)

Success$StartDrivers<-Drivers.PR
Success$BatchSize<-NPassengers
Success$Flexibles<-NMixed
Success$DriversOnly<-NDrivers
Success$NumBatches<-NBatches
Success$NumDays<-NDays
Success$AddPassengers<-AddPassengers
Success$ClusterSize<-NumberperCluster
Success$DriverSeats<-Passengers
Success$TimeGap<-Minutes
Success$DistHome<-DistanceHome
Success$DistWork<-DistanceWork
Success$DistTotal<-TotalWalk
Success$SocialChance<-Chance
Success$No.Match<-NoMatch
Success$Yes.Match<-Yes.Match

for(i in 1:nrow(Success)){
Success$TotalDistance[i]<-Output.T[i]
Success$P1Distance[i]<-Output.Total[i]
}

outfile<-paste0("Results/Case3ResultsB.txt")

write.table(Success,outfile,append=TRUE,sep="\t",col.names=FALSE)
#Close out seed
}
#Close out population size changes
}
}
}
}

}
}
```