EVALUATING WIDER IMPACTS OF TRANSPORT USING AN INTEGRATED URBAN CGE MODEL

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF SOCIAL SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ÖZHAN YILMAZ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
THE DEPARTMENT OF ECONOMICS

AUGUST 2018

Approval of the Graduate School of Social Sciences

Prof. Dr. Tülin GENÇÖZ
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Doctor of Philosophy.

Prof. Dr. Meltem DAYIOĞLU TAYFUR
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Doctor of Philosophy.

Prof. Dr. Ebru VOYVODA
Supervisor

Examining Committee Members

Prof. Dr. Erinç Yeldan	(Bilkent Uni., ECON)
Prof. Dr. Ebru Voyvoda	(METU, ECON)
Prof. Dr. Jean Mercenier	(Paris II Uni., ECON)
Prof. Dr. Işıl Erol	(Özyeğin Uni., IF)
Assoc. Prof. Dr. Serkan Küçükşenel	(METU, ECON)

PLAGIARISM

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Özhan Yılmaz

Signature :

ABSTRACT

EVALUATING WIDER IMPACTS OF TRANSPORT USING AN INTEGRATED URBAN CGE MODEL

Yılmaz, Özhan
Ph.D., Department of Economics
Supervisor : Prof. Dr. Ebru Voyvoda

August 2018, 163 pages

This study follows the literature that utilizes a more hybrid approach to grasp the heterogeneity among different agents in an urban context. Such an integrated approach can handle impacts of transport policies comprehensively, while simultaneously capturing the behavioural heterogeneity of different agents. This is achieved by adding model components capturing key theoretical elements of discrete choice theory into an applied general equilibrium model. “Full integration”, where all blocks of models run simultaneously to find an equilibrium, makes distinct this study from the similar ones.

After testing the proposed model using a pseudo data set, and different household categorisation settings and scenarios, I applied it to evaluate effects of London’s planned Crossrail 2 project, which aims at connecting North and South London rail systems. I used London Travel Demand Survey (LTDS) micro-data in the analysis. Model results show that rental price would increase significantly in certain boroughs (Waltham Forest, Merton, Barnet, Enfield and Kingston upon Thames) where the project improves the public transport accessibility. The total increase in public transport ridership by 32,280 leads to a 6 per cent increase the public transport use in commuting. Model results show that number of households in boroughs, in which public transport accessibility is improved due to the Crossrail 2 project, increases while central boroughs lose a considerable number of households to these boroughs.

Leaving aside the innovation it offers, the key outcome of this study is the required accumulation of knowledge and motivation for future studies in fully-integrated urban CGE models. Findings of this research and newly introduced approaches and methods can be used to develop a more comprehensive model employing all the capabilities of CGE and urban transport modelling.

Keywords: Computable General Equilibrium, Applied General Equilibrium, Discrete Choice Models, Full Integration, Crossrail 2 Project

ÖZ

ULAŞIMIN GENİŞ ETKİLERİNİN KENTSEL BİR CGE MODELİ KULLANILARAK DEĞERLENDİRİLMESİ

Yılmaz, Özhan
Doktora, İktisat Bölümü
Tez Yöneticisi : Prof. Dr. Ebru Voyvoda

Ağustos 2018, 163 sayfa

Bu çalışma, ekonomik birimler arasındaki heterojenliği kent ölçeğinde ele almak amacıyla hibrit yaklaşımı kullanan literatürü takip etmektedir. Böyle bir yaklaşım, farklı birimler arasındaki davranışsal farklılıkları dikkate alarak ulaşım politikalarının daha kapsamlı bir şekilde incelenmesine olanak sağlamaktadır. Bu, ayrık seçim teorisi temelli model bileşenlerinin hesaplanabilir genel denge modeline eklenmesiyle sağlanmaktadır. Bütün model bloklarının dengeyi bulmak amacıyla aynı anda çalıştığı "Tam Entegrasyon" yapısı, bu çalışmayı literatürdeki diğer çalışmalardan ayrıştırmaktadır.

Önerilen model, pseudo-veri, farklı hanehalkı kategorileri ve senaryolar kullanılarak test edildikten sonra, Londra'da yapılması planlanan ve Kuzey ve Güney demiryolu ağlarını birleştirmeyi amaçlayan Crossrail 2 projesini değerlendirmek için kullanılmıştır. Analizler için Londra Ulaşım Talep Anketi mikro verileri kullanılmıştır. Model sonuçları, proje sonucunda toplu taşıma erişilebilirliği artan bölgelerde (Waltham Forest, Merton, Barnet, Enfield ve Kingston upon Thames) konut fiyatlarında önemli ölçüde artış olduğunu göstermektedir. Toplu taşıma kullanımı da günlük 32.280 artışla yüzde 6 oranında artmaktadır. Model sonuçlarına göre, Crossrail 2 projesi sonucunda toplu taşıma erişilebilirliği artan bölgelerde hanehalkı sayısı artarken, kent merkezindeki bölgelerdeki hanehalkı sayısı azalmaktadır.

Bu alanda getirmiş olduğu yeniliğin ötesinde, bu çalışmanın asıl çıktısı tam entegrasyona dayalı kentsel CGE modellerinin geliştirilmesine yönelik bilgi ve motivasyonun gelişimine olan katkısıdır. Bu çalışmadaki bulgular ile ilk kez önerilen yaklaşım ve metodlar, CGE modelleri ve kentsel ulaşım modellerinin tüm yetkinliklerini kullanan daha kapsamlı modellerin oluşturulmasında kullanılabilecektir.

Anahtar Kelimeler: Hesaplanabilir Genel Denge, Ayrık Seçim Modelleri, Tam Entegrasyon, Crossrail 2 Projesi

DEDICATION

To Arhan

ACKNOWLEDGMENTS

First and foremost, my deepest gratitude goes to my supervisor Prof. Dr. Ebru Voyvoda for her guidance, advice, criticism, encouragements and insight throughout the research.

I would would also like to thank Prof. Dr. Işıl Erol for her guidance and encouragement at the very early stages of this study and feedbacks in thesis supervising committee meetings. I would also like to thank Assoc. Prof. Dr. Serkan Küçükşenel for his suggestions and comments in thesis supervising committee meetings.

The cooperative attitude of Transport for London (TfL) in data sharing is gratefully acknowledged.

Many thanks to my family – Selen and Arhan. Thank you!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CBA	Cost-Benefit Assessment
CBD	Central Business District
CD	Continuous Demand
CES	Constant Elasticity of Substitution
CET	Constant Elasticity of Transformation
CGE	Computable General Equilibrium
DC	Discrete Choice
EC	European Commission
GDP	Gross Domestic Product
GEV	Generalized Extreme Value
GLA	Greater London Authority
LTDS	London Travel Demand Survey
MMRF	Monash Multi-Region Forecasting
MNL	Multinomial Logit
MSA	Metropolitan Statistical Area
OD	Origin-Destination
RELU-TRAN	Regional Economy, Land Use and Transportation Model
SAM	Social Accounting Matrix
SO	Social Optimal
TAP	Traffic Assignment Problem
TEN-T	Trans-European Transport Networks
TFI	Technological Fuel Intensity
TfL	Transport for London
UE	User Equilibrium
VA	Value Added
VOA	Valuation Office Agency
WEZ	Western Extension Zone

CHAPTER 1

INTRODUCTION

Although it cannot be classified as a final good or service (with a few exceptions like cruise travels) transport is a key driver of economic activity. Without an adequate transport network (or infrastructure), one cannot mention proper functioning of markets. Transport infrastructure provides transmission channels for goods and services required by people and industries and lets industries to reach labour force they need in their production processes. People commute to their works, go to hospitals, schools and public institutions to get health, education and other public services or travel to some shopping districts thanks to the accessibility provided by transport networks of cities. Like most physical networks, transport networks are exposed to severe efficiency problems led by ineffective mechanisms in prioritising higher value trips (freight and service vehicles) or space efficient trips (public transport, high occupant vehicles). In most cases without scarcity in capacity, excess capacity tolerates these problems and we often do not notice this mechanism. So is the case for transport networks. However, urbanisation, accompanied by the economic development of cities, requires more than provided additional capacity to deal with the increasing pressure on transport infrastructures. This pressure, in cities with barely adequate level (or inadequate level) of capacity, often leads to capacity shortages. So, traffic congestion problem becomes an example to the infrastructural capacity shortage in cities. The transport system of a city, indeed, shall be deemed to be the Achilles' heel, as transport is affected not only by increasing population but also increases in the number of trips, origin and destination points creating urban traffic and land use demand.

The issues of urban traffic congestion and its externalities have been among the top priorities of major cities and, several projects have been performed or planned to respond to the problem. How successful cities are in reducing traffic congestion (and/or increasing public transport ridership) is heavily under debate, as traffic is not getting better in these cities, according to some indices for traffic conditions. To give an example, according to the TomTom Traffic Index: Measuring Congestion Worldwide, regarding overall congestion level[1] among major cities, Mexico City (Mexico) tops the list with a congestion level of 66 per cent, passing two Asian cities Bangkok (Thailand) and Jakarta (Indonesia) with the levels of 61 percent and 58 percent, respectively.

Despite many mega infrastructure projects, increasing traffic congestion urges the need to plan urban transport better. It is obvious that better planning requires better tools, but we need better tools in what aspects? One can argue that assessment of transport policies and projects are focused on a few specific questions trying to find answers for costs and benefits of these. However, such questions would probably lead us to work with aggregates (and averages) leaving every kind of disparities aside. To give an example, how can we qualify a congestion pricing scheme or a traffic pollution charging scheme as successful if the policy impedes access to the job market for low-income people, particularly for women, living on outskirts of a city without an adequate public transport infrastructure? In other words, are we sure about the possible burdens of candidate policies lay on different groups of people, and individuals' responses to reduce the effects of these burdens? Policymakers should evaluate candidate policies, also asking questions such as: whether the proposed policy causes a change in expenditure structure of low income people residing at a specific location and the effect of this policy on working decisions of a specific group of people, or the impact of unskilled immigrants on road traffic and the parts of the city that would require investment in the future due to the sharp increase in population. That's to say, the problem laid demand complementary analyses that would raise the capability of policymakers assessing transport policies in a more comprehensive and equitable way considering impacts on different groups. Such analyses require going into details of heterogeneity among people, and so, should make use of both micro and macro-level data that are available to researchers.

As Graham (2007) discusses, standard cost and benefit appraisal methods do not address economic impacts of transport policies and investments completely.

---

[1] Increase in overall travel time when compared to an uncongested situation.

Microsimulation models can model households' and firms' behaviours using micro-level data (Robilliard et al., 2001). However, these models are partial equilibrium models and they only consider the household side of the economy (Peichl, 2008). On the other hand, general equilibrium models are generally able to provide insights into market mechanisms allocating resources on mutually interdependent markets. They use a few numbers of (or only one) representative agents (Peichl, 2008). Therefore, they are unable to grasp possible heterogeneity among agents and their behavioural responses to policy changes. In order to internalise transport externalities and distribution of impacts among different economic agents, integrating general equilibrium models with microsimulation models is considered to be a promising method with substantial potential to close this gap.

To this end, models integrating economic models and household choice models based on discrete choice theory might be a promising field to evaluate wider economic impacts of transport policies while considering heterogenous economic agents. Computable General Equilibrium (CGE) models (or Applied General Equilibrium models) provide a good mathematical framework that can accommodate different types of models.

Employing CGE models in transport-related research questions (impact assessment studies, in particular) has become more alluring recently. The literature is still in its infancy, but the weaknesses of traditional cost-benefit assessment (CBA) analyses in transport studies in internalisation of transport externalities and distribution of impacts among economic agents are often referred to explain this trend (Robson and Dixit, 2015). Considering the central role of transport activities throughout the economy, these weaknesses become too important to be neglected, particularly for mega public projects in transport relying on taxpayers' money. Proposing a more comprehensive approach with solid economic foundations, applied general equilibrium models are often preferred to evaluate, not only direct impacts of projects but also indirect impacts of them. Yet, these models turn out to be highly complex and require a substantial amount of consistent data.

The models in the literature can be classified with respect to different attributes, such as classification in terms of the geographical unit the models are applied: (i) regional models and (ii) urban models (Robson and Dixit, 2015) and the portion of the economy transport is assumed to influence: (i) production activities, where transport is treated as an industry or a cost item resulting from transfers, (ii) discrete choice decisions (location choice, in particular) of economic agents (particularly households). The literature shows that these two different approaches in the classification of transport CGE models have similarities with each other.

Regional CGE models, in which the focal area is trade in general, are often used to assess impacts of transport policies and investment projects at regional scale. They represent the interaction among different regions using multi-regional social accounting matrices (SAMs). High level transport networks are the transport contexts of these models. Therefore, strategic transport networks (for example, TEN-T network) are often used in these models rather than urban transport networks.

The context of an urban CGE model is the urban area. This kind of models is good to assess impacts of transport policies and investment projects on behavioural change of economic agents (households or individual travellers, in particular). Therefore, key parameters in urban transport modelling like location (residential, working), transport mode and route choices of agents become an integral part of these models. This integration is often established in a form of “loose integration” where transport models provide transport figures (travel time and cost) to the CGE model as inputs in an iterative procedure.

This study follows the literature that utilizes a more hybrid approach to grasp the heterogeneity among different agents in an urban context. This approach is useful to endogenize interactions among different markets in a single framework. Such an integrated approach can handle impacts of transport policies comprehensively, while simultaneously capturing the behavioural heterogeneity of different agents. This is achieved by adding model components capturing key theoretical elements of discrete choice theory into an applied general equilibrium model.

The primary goal of the Thesis is to develop a comprehensive modelling framework to analyse impacts of urban transport policies on different groups of people. A macroeconomic model of the urban-CGE tradition (based on the applied general equilibrium modelling and extended in spatial dimension) is integrated with a household choice model (based on discrete choice theory) and a travel model (based on Wardropian equilibrium). The proposed integration procedure is the "full integration" where three sub-models (economic, household choice and travel models) run simultaneously. The model employs disaggregate level data at household scale. The primary agents of the model are the individual households that are heterogeneous in many respects including household skills, household preferences on residential locations and transportation mode for commuting purpose.

It's expected that the proposed framework would contribute to planning where economic, social, demographic and land-use consequences of transport policies and investment projects are duly assessed. This will help us to design transport policies and plan investment projects alleviating negative externalities of current household location choices and mobility patterns while considering impacts of these policies and projects on heterogenous of people.

The primary objective of this research is developing and testing the feasibility of a fully-integrated urban CGE model to assess wider impacts of transport policies and projects. Secondary objectives can be listed as follows: (i) to identify data and workload requirements for developing a fully-integrated urban CGE model, (ii) to identify challenges and potential ways to overcome these challenges, and (iii) to provide another option in transport (and land use) planning for decision makers.

The thesis provides several innovations at different levels. These can be outlined in four main pillars as follows:

1) Comprehensiveness: Considering bidirectional interactions between the pairs of the economy, land use and transport enable us to develop an integrated model capable of illustrating impacts of different policies on different markets and factor utilisation.
2) Integration: Transport model is transformed into a set of equations using a new method. By this way, the model becomes a set of equations for blocks of different sub-modules, which run simultaneously rather than in iterations. This makes it a fully-integrated model ensuring equilibrium values.
3) Heterogeneity level of economic agents: Disaggregate level of economic agents is employed in the model. This will contribute to

understanding how different types of agents differ in their behavioural responses (housing location choice, in particular).

4) Implementation: At the last but not the least, a real case (Crossrail 2 Project) in London is assessed using real data (household surveys). This kind of implementation at this scale provides several implications about the use of fully-integrated models for large networks.

The organisation of the Thesis is as follows.

This chapter provides a brief introduction to arising problems in urban transport and needs to use comprehensive tools to tackle these problems. This conceptual discussion is followed by a literature review providing key CGE studies in transport appraisal, and as well as the Thesis organisation.

Chapter 2 is the modelling approach chapter. This explains model specifications for households and firms. I elaborate the procedure for integrating three models (economic model, household choice model and travel model) and data requirements in this chapter.

Chapter 3 tests the proposed integrated model using a pseudo data set of a representative urban unit with four districts. In the scenario analysis part of this chapter, I evaluate a set of alternative transport policies (i.e. capacity increase in private transport, public transport improvement, cordon pricing) and analyse the impacts of such policies on a set of parameters including household locational distribution, demand on consumption goods and housing, and housing prices.

Chapter 4 introduces the urban CGE model constructed to analyse wider impacts of transport policies to be applied in Greater London Area (GLA). The constructed model is used to analyse impacts of planned Crossrail 2 project.

The Conclusion chapter concludes the Thesis by providing concluding remarks and recommendations for future studies.

CHAPTER 2

MODELLING APPROACH

2.1 Introduction

There are different CGE modelling approaches in transport appraisal. Following the classification approach proposed by Robson and Dixit (2015), these approaches can be classified into two broad classes: (i) Regional CGE Models and (ii) Urban CGE Models. The focal area in regional models is trade activities taking place on strategic transport networks while urban CGE models have close interaction with urban transport modelling where movement of people on a congested network is the primary concern.

2.1.1 Regional CGE Models

CGE modelling has a long history in regional science. These models are employed for transport appraisals at a regional scale or even an international scale like CGEurope (Bröcker, 1998) and RHOMOLO (Mercenier et al., 2016). A typical regional model aims at forecasting socio-economic and spatial impacts of big transport projects having an impact on the accessibility of several regions like Trans-European Network (TEN) projects for transport.

In this modelling approach, multi-regional social accounting matrices are employed to represent each region and produce regional indicators (regional GDP, regional employment, regional accessibility, etc.) to assess impacts at regional scale. The aim of these models is to represent the interaction between regions, therefore, urban transport networks are not considered but the strategic ones connecting regions. For this reason, traffic congestion is avoided in analyses and travel cost is linked to travel distance.

Bröcker has contributed significantly to the literature on the application of CGE models in transport appraisal. One of the most influential innovations of Bröcker

(1998) model is the introduction of "transport agents", carrying out transport activities in an economy, along with usual economic agents: producers and households. Transport then is related only to business activities rather than personal affairs. In Bröcker (2002), private passenger travels are considered along with business related travels. Transport activities and associated costs are treated in a completely different manner in Bröcker et al. (2004). In this study, Samuelson's (1954) well-known iceberg transport cost model, which suggests a cost function that is a linear function of the distance, is adopted. This approach is also inherited in Bröcker et al. (2010), in which geographical trade cost of a commodity is correlated with the transfer distance. Influenced by Bröcker (2002), Zhu et al. (2012) analyse wider economic impacts of selected transport (building HS2 and dualling A11) and land use (releasing Green Belt) policies for London and surrounding areas using a static CGE model for an open economy with more industry and trade flavours rather than urban issues.

The European Commission's (EC) RHOMOLO model is another example of spatial CGE model used for regional studies. The model is a traditional CGE model with a special focus on spatial interactions among 267 regions. These interactions cover trade of goods and services, capital mobility, interregional investments and knowledge spill-overs. Transport costs are only for trade activities with the iceberg type and introduced to the model as an asymmetric trade cost matrix, which is derived from EC TRANSTOOLS transport model. (Mercenier et al., 2016) RHOMOLO model is mainly used for cohesion policy impact assessment purposes. As for shocks to the model, it employs a variety of policies including investment support for transport infrastructure, human capital and innovation. (Boeters et al., 2017) Oosterhaven and Knaap (2003) uses a CGE model (RAEM) of Knaap and Oosterhaven (2000) to evaluate impacts of six different rail connection alternatives for linking Groningen City and Schiphol Airport along with the reference scenario. Authors revise this study in Knaap and Oosterhaven (2011) with minor changes in welfare gains offered by the alternative scenarios.

Unlike many regional models (like urban transport models, dialectically in this term) Kim et al. (2004) proposes an integrated framework with a dynamic CGE model accompanying with a transport model, which measures accessibility changes as consequences of highway projects, to evaluate highway projects in terms of economic growth and regional disparity in South Korea.

Household demand for transport services is investigated with a perspective of energy issues in Berg (2007) where households and producers are subject to energy and environmental taxation in the model framework.

Verikios and Zhang (2015) apply a comparative-static multi-region CGE model (MMRF – Monash Multi-Region Forecasting) and a microsimulation model together to quantify direct and indirect effects of structural changes in Australian urban transport industries. They split Australia into eight regions and observe the effects of these changes at the micro level (households). In this study, urban transport is taken as a regulated industry.

2.1.2 Urban CGE Models

Unlike regional CGE models, which often focus on trade-related issues, urban CGE models mostly are more on the impact on the behavioural side. Thus, discrete choices that decision-makers face, such as the choice of residential or working locations of households, are the main concerns of these models. Transport modelling is another key part of urban models. Unlike regional models, in which simplified transport networks might be enough to represent regional transport activities, traffic congestion and its externalities necessitate considering different household decisions like mode choice and route choice decisions in urban models.

There are several scholars producing significant contributions. Among these, Alex Anas is to be cited as one of the earliest contributors in designing discrete choice model applications in transport studies (Anas, 1982). He has developed the Regional Economy, Land Use and Transportation Model (RELU-TRAN), a spatial CGE model to evaluate the impacts of implemented transport (and land-use) policies on metropolitan areas, in collaboration with several scholars [Anas and Kim (1996), Anas and Xu (1999), Anas and Liu (2007), Anas and Hiramatsu (2012), Anas (2013a), Anas (2013b), Anas and Hiramatsu (2013)].

Horridge (1994) handles urban transport problem using a simpler but very effective modelling approach benefiting from the core implications obtained from the discrete choice theory. He introduces an urban CGE model to evaluate impacts of certain scenarios to be applied in Melbourne, Australia. In this model, multinomial logit (MNL) probability of selecting any housing and working locations pair is used to determine the share of each pair of all pairs, thus paving the way to calculate market shares. These aggregates are then inserted into a general equilibrium model, influencing market dynamics in a way to take people's decisions into account. This aggregation approach is investigated by Magnani and Mercenier (2009) thoroughly. To integrate partial equilibrium and CGE models, they propose to use exact aggregation method where heterogeneous individuals are aggregated into a representative agent. They show that, under certain conditions for the labour market, aggregating discrete choice probabilities of a large set of statistically identical and independent individuals gives the same aggregate labour supply function derived by optimising a single agent with constant elasticity of transformation (CET) function.

Sato and Hino (2005) propose a CGE model to evaluate long-term land use, regional economy and transport effects of the congestion charging scheme to be applied in central Tokyo. In the proposed model, probabilities for location choices of households and businesses are calculated using logit models. Proposed CGE model is coupled with a general 4-step travel model to model travel preferences.

Rutherford and van Nieuwkoop (2011) suggest an urban transport CGE model to evaluate impacts of high skilled labour inflow to Zurich on different markets in a simple economy with economic agents of households and producers.

Truong and Hensher (2012) propose a method integrating discrete choice (DC) models and continuous demand (CD) models in CGE framework to evaluate wider economic impacts of a transport project in Sydney. Transport is considered as a service sector or a cost item that should be borne by producers mostly in regional models, while, in urban models, it is an important factor changing the accessibility of locations so choices of decision makers.

Indeed, the most influential feature of transport doesn't lurk in monetary terms, neither being a sector nor a cost item, but in the accessibility that it provides to each agent in an economy. Accessibility has a central role in people's decision-making mechanism. As far as the transport (urban transport in particular) is concerned, a representative agent in a classical CGE model cannot deal with accessibility, which lies at the heart of our problem.

At this point, behavioural models based on discrete choice theory offer great potential to grasp heterogeneity among agents. As discussed in Horridge (1994), Magnani and Mercenier (2009) and Truong and Hensher (2012), establishing the link between disaggregate discrete choice models and aggregate CGE models is key to construct integrated models.

This study introduces a framework to represent and analyse heterogeneity in different agents and to endogenize interactions among different markets in the single mathematical framework. The integrated approach proposed, while simultaneously capturing the behavioural heterogeneity of different agents, aims at handling impacts of transport policies comprehensively. This interaction is achieved by adding model components capturing key theoretical elements of discrete choice theory into a CGE model. Besides this integration, a travel model based on Wardrop's First Principle (user equilibrium) is embedded into the mathematical framework. Such an integration makes the proposed model perform three different tasks (economic, household choice and transport modelling) in a single framework without sequential simulation runs searching for a predetermined level of convergence.

This section is an introduction to the modelling approach that is proposed to construct a model integrating an economic model with a household choice model and a travel model. Section 2 introduces the adopted modelling approach and key assumptions in constructing the model. Section 3 provides detailed information on model specifications for economic agents. In this section, I explain theoretical foundations of the integrated model. Section 4 discusses fundamental mathematical equations framing problems of household location and mode choice, traffic equilibrium and general equilibrium and provides a list of market clearing equations. Section 5 concludes this Chapter by providing specific recommendations on future studies based on this conceptual framework accompanying with limitations of this study and general recommendations on some policy issues.

2.2 Modelling Approach

This Section proposes, an urban CGE model with heterogeneous households and firms[2]. Households are assumed to be the owners of dwellings and capital stock, so households benefit from unearned income generated by renting these assets. Firms carry out their production activities.

Transport enters in two ways into the model proposed. On one hand, transport is part of households' utility problem via the disutility of the time spent on journeys. On the other hand, transport costs are considered in the budget constraints of households. Travel activities, therefore, have negative impacts on household's utility level, particularly for people whose residential locations are far away from their working locations. Using this modelling approach, one would ensure the formation of a balance between housing and transport costs of each household. Otherwise, failing to represent one of the two cost items would lead the model to generate unexpected (and implausible) results. To give an example, without any transport cost, households would choose inexpensive housing locations regardless of their working locations or households would want to reside as close as possible to their working locations to minimise transport effects on their utilities in case of incurring no housing cost.

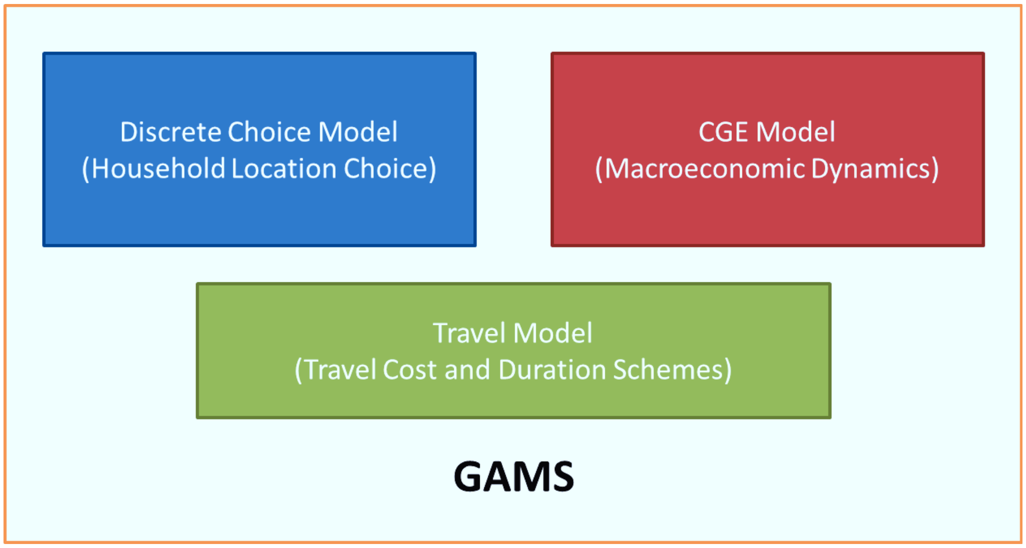


Figure 2.1 Integration approach of models

---

[2] Government, landlords or any other decision makers are neglected in the model framework.

A travel model, which provides travel times between the specified nodes in the city, is embedded into the CGE model. By this approach, extra traffic created by the relocation of people can be loaded into the congested network, and vice versa.

I assume that there is no change in population pool and existing households do not change their working locations. This means that discrete choices of households are residential locations and transport modes they will use for commuting. Producers are assumed to be fixed at their operational locations as well. This makes the model a residential location choice model in a CGE framework.

2.3 Model Specifications

The model has two different economic decision makers: (i) Households and (ii) Firms. Households decide on their housing locations, transport mode and expenditures on housing, goods and services. Firms are cost minimizers. They decide on the amount of factors to production they will use for a certain level of output. Firms are assumed to be immobile and not exposed to transport costs. The integrated framework is composed of three sub-models running simultaneously:

1) **Household Choice Model** determines the probabilities of selecting specific residential locations and transport modes for the travels between residential locations and working locations. Discrete Choice Theory is used to calculate these probabilities. Household utility functions that are used to calculate choice probabilities include both utility components priced at markets and unpriced ones. Consumption demand on housing, goods and services are priced at respective markets. However, utility components neighbourhood’s attractiveness and disutility of travel time are not priced at markets. Parameters of these elements are calibrated using initial values.
2) **Transport Model** calculates the travel time and travel cost required for journeys between relevant OD (origin-destination) pairs. Main input of this sub-model is the number of households for each OD pair.
3) **CGE Model** is comparative-static. It calculates the impacts (market prices, factor utilisation, output) of a policy shock (policy change, project, etc.) to compare two future states models (without shock/with shock).

See Appendix A for the full list of parameters and variables of the model.

2.3.1 Network and Travel Model

The Household Choice Model uses the travel times of commutes and the CGE Model uses associated costs for these travels exogenously. Households use these parameters in their own decisions of consumption, housing location and travel mode choices. It is important to model travel activities on a transport network, although utilising observed data on travel costs and times in economic models is an option. However, one should bear in mind that this option comes with a severe cost: neglecting effects of people's residential location choices on the transport network. Instead, establishing a bidirectional link between the economic model and the travel model is preferred. This link can be formed in two possible ways: an "easy" (but messy at the same time) way with a "loose integration" of two models searching for a level of convergence through solving both models iteratively[3] and a "hard" way with full integration of two models, which requires modelling different models as sub-models in a single mathematical framework. In this study, the latter way is used. Thus, a travel model, which is based on Wardrop's First Principle (1952), is formulated along with the CGE model and household location choice model.

Explicitly emphasizing the need for a theoretical model of traffic, Wardrop (1952) introduced road traffic equilibrium principles, which constitute foundations of many travel models. In his seminal study, Wardrop elaborates on two alternative criteria in determining route assignments:

> (1) The journey times on all the routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused route.
> (2) The average journey time is a minimum (p.345)

The first criterion, Wardrop's First Principle, proposes that traffic reaches an equilibrium state where no driver can reduce travel time (be better off) by choosing another route. This principle is often attributed to "user equilibrium (UE)" in the literature. This criterion is explained by Wardrop (1952) as follows: "The first criterion is quite a likely one in practice since it might be assumed that traffic will tend to settle

---

[3] One should note that convergence is not always guaranteed in iterative solutions procedures.

down into an equilibrium situation in which no driver can reduce his journey time by choosing a new route." (p.345)[4]

The second criterion (Wardrop's Second Principle), indicates that a driver behaves in cooperation with the others ensuring the most efficient utilisation of a transport network. Drivers' choices lead to the "system optimal (SO)". In practice, this condition is unlikely to be achieved without such an outside intervention like a tolling system (Holden, 1989). The First Principle is formulated as in the following link-route representation using travel time function of LeBlanc et al. (1975) where total travel time along an arc is a function of free flow travel time and additional time required due to increasing traffic density:

$$\min z(x) = \sum_a \int_0^{x_a} \mathrm{A}_a + \mathrm{B}_a \left[\frac{x}{Q_a} \right]^4 dx \tag{1}$$

$s.t.$

where A is the time required to traverse a link under no traffic condition, B is the traffic congestion coefficient, *x* is traffic flow and *Q* is the link capacity.

(1) Sum of traffic flows on different paths for specific journeys from *i* to *w* equals to travel demand from *i* to *w*:

$$\sum_{path} f_{path}^{iw} = q_{iw} \left(f_{path}^{iw} \geq 0 \right) \tag{2}$$

where *f* is traffic flow on a path and *q* is travel demand for specific origin-destination (OD) pairs.

(2) Sum of all traffic flows using a link equals to traffic flow on this link:

$$x_a = \sum_i \sum_w \sum_{path} f_{path}^{iw} \cdot \Delta_{a,path}^{iw} \tag{3}$$

where, $\Delta_{a,path}^{iw}$ is the link-path incidence parameter (1 if link *a* is in the path from *i* to *w*, 0 o/w).

---

[4] In Holden (1989), this explanation is claimed to be another principle (Wardrop's Third Principle) after explaining key differences between Wardrop's First Principle and the above statement.

Although embedding household location choice model into the CGE framework is straightforward using probabilities to calculate market shares of each discrete choice (See Horridge, 1994; Truong and Hensher, 2012), embedding travel model is hard and requires travel model to be converted into a set of simultaneous equations as opposed to an optimization problem. For doing this, I propose a new method, which ensures the unique optimal solution of the UE model, to do this conversion as follows (See Appendix B for a brief explanation and proof):

(1) Equation (2)

(2) Equation (3)

(3) Travel time on a link is calculated using a convex non-decreasing function:

$$t_a = \mathrm{A}_a + \mathrm{B}_a \left[\frac{x_a}{Q_a} \right]^4 \tag{4}$$

(4) The total travel time of a path from *i* to *w* equals to the sum of travel times of all links belonging to this path (link-path incidence parameter Δ is given):

$$t_{path}^{iw} = \sum_a t_a \cdot \Delta_{a,path}^{iw} \tag{5}$$

(5) If a path is used for travelling from *i* to *w* travel time of this path will be equal to any path that is used for travelling from *i* to *w* (Wardrop's First Principle) where $\pi(i,w)$ is the number of different paths used for a journey:

$$t_{path=1}^{iw} = \sum_{path} \frac{t_{path}^{iw}}{\pi(i,w)} = \tau_{iwm} \tag{6}$$

In this setting, link-path incidence parameter Δ is treated as an exogeneous parameter, which is calculated by solving TAP with changing transport conditions and later verified using an algorithm. (See Appendix C for the verifying algorithm)

Although the above model provides travel time information varying with traffic congestion level on each link, it doesn't give information on the monetary cost of travel. This requires defining an additional travel cost function for travel costs, mainly based on fuel consumptions of vehicles. There are, in the transport literature, some empirical studies investigating the effect of congestion on fuel consumption. These studies, in general, indicate that traffic congestion leads to increase in fuel consumption of vehicles; however, traffic congestion's effect on fuel consumption is limited when compared to its effect on journey times (Treiber et al., 2007). This effect is modelled for private transport mode using the following formula assuming fuel consumption increases linearly between two reference points.

$$\kappa_{iwm='1'} = \left[C^f + \frac{\tau_{iwm='1'}}{\tau^f_{iwm='1'}} \frac{t^f_{100}}{t^c_{100}} \left(C^c - C^f \right) \right] \cdot D_{iw} \cdot p^f \tag{7}$$

where, C^f is the fuel consumption under no congestion condition, C^c is the fuel consumption under a reference congestion level, τ^f_{iwm} is the travel time under no congestion, t^f_{100} is the reference travel time under no congestion condition (hour/100 km), t^c_{100} is the reference travel time under a reference congestion level (hour/100 km), D_{iw} is the distance and p^f is the fuel cost per litre.

Other travel modes are assumed to be not exposed to negative effects of traffic congestion. Therefore, one can list and utilize the travel times and costs for each of the other mode (list) in pre-determined static travel matrices[5].

2.3.2 Households

Households are categorised according to their residential location (*i*), working location (*w*), preferred commuting mode (*m*) and skill level[6] (*g*). The indices for residential and working locations for households denote the regions in the boundaries of the city to be studied. Households with no working location would have the index value "0", $w = 0$. The commuting mode is divided into four categories: (i) non-commuting, (ii) car, (iii) public transport and (iv) other transport modes (including non-motorised transport). In the classification of households, 3 types of skill levels are

---

[5] However, traffic congestion would affect bus routes without any dedicate lanes or bus priority schemes. In these cases, travel times on arcs, which are produced by the travel model, can be used to estimate travel times of buses floating along each route. This time, instead of using generated OD travel time and cost schemes, travel time and cost values for relevant arcs should be aggregated in line with predetermined bus routes.

[6] Varying indices can be used to categorise households. See Chapter 3 for the use of income levels instead of household skills.

defined for households. These skills are: (i) non-working (unemployed, retired), (ii) non-qualified (low skilled) working and (iii) qualified (high skilled) working.

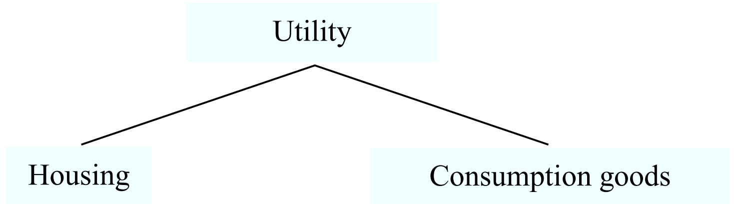


Figure 2.2 CES household utility function

Households maximise their utilities in accordance with a constant-elasticity-of-substitution (CES) utility function. The utility function is assumed to be composed of two types of units: (i) housing and (ii) consumption goods (commodities), which includes any other goods and services consumed by the consumers (Figure 2.2).

Considering household trips as consumption goods (or services) providing households with some level of utility would be misleading as transport is not a final product but an intermediary activity to attain such goals. However, residential location choice (or employment location choice) of any individual would cause a certain level of travel cost depending on distance, preferred travelling mode and congestion level on the preferred route. Besides, households attain some utility choosing their housing locations. This may come from the existing reputation of this neighbourhood or accessibility to other facilities and activities.

We would rewrite the household utility including the elements of "utility of neighbourhood" and "disutility of travelling" as follows[7]:

$$U_{iwmg}\left(d,c\right)=\left[\sum_{l=1}^{n}\alpha_{iwmg}^{l}c_{iwmg,l}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right]^{1/\rho}+\Psi_{i}-\gamma_{iwmg}\tau_{iwm} \tag{8}$$

where α is the share parameter, c and d are consumptions of commodities and housing spaces respectively, Ψ is the utility of neighbourhood, γ is disutility of travelling and τ is travel time, while $\rho=\left(\sigma-1\right)/\sigma$ and σ stands for the elasticity of substitution between the housing and the consumption goods for any household. Note that costs

---

[7] See Anas and Liu (2007) and Anas and Hiramatsu (2013) for constant utility effects of choices.

and times associated with commuting are not exogenous parameters, but they are calculated endogenously by the transport column of the model.

Transport has a monetary cost shrinking the household budget. Hence, household budget constraint can be written as:

$$-M_{iwmg} + r_i d_{iwmg} + \sum_{l=1}^{n} p_l c_{iwmg,l} + \kappa_{iwm} \leq 0 \tag{9}$$

where, M is the total household income, r is the unit rental rate for housing, p is the price of commodities and κ is travelling cost. Here, it should be noted that rental rates are varying by locations while the price level for consumption goods is the same for all locations.

As previously mentioned, households own the capital stock in the economy and they lend this factor to the firms for production activities. In return, firms will pay profit rate for the capital they use. Households also own dwellings, like capitals, to be rented. However, it is to be noted that a dwelling that a household owns can be rented to any household including the owner of that dwelling. Therefore, as the first step, we can write the household budget as follows:

$$M_{iwmg} = w_g + \delta e^{K}_{iwmg} + \sum_{i'} r_{i'} e^{H}_{iwmg}\left(i'\right) \tag{10}$$

where, w is earned income of households and δ is the capital price, while e indicates capital and housing endowments of households. It should be noted that the new index (i') is introduced to address households' dwelling (housing) possessions at location i'. The Lagrangian of the problem can be stated in the following form:

$$\mathcal{L}(d,c,\lambda) = \underbrace{\left[\sum_{l=1}^{n} \alpha^{l}_{iwmg} c^{\rho}_{iwmg,l} + \alpha^{h}_{iwmg} d^{\rho}_{iwmg}\right]^{1/\rho} + \Psi_i - \gamma_{iwmg}\tau_{iwm}}_{U_{iwmg}(d,c)} + \lambda\left[M_{iwmg} - r_i d_{iwmg} - \sum_{l=1}^{n} p_l c_{iwmg,l} - \kappa_{iwm}\right] \tag{11}$$

where λ is the Lagrange multiplier. Taking the derivatives of the Lagrangian with respect to decision variables d and c, and the Lagrange multiplier λ leads to the following first-order conditions:

$$(d) \quad \alpha^{h}_{iwmg}\left[\sum_{l=1}^{n} \alpha^{l}_{iwmg} c^{\rho}_{iwmg,l} + \alpha^{h}_{iwmg} d^{\rho}_{iwmg}\right]^{(1-\rho)/\rho} d^{\rho-1}_{iwmg} - \lambda r_i = 0 \tag{12}$$

$$(c) \quad \alpha^{l}_{iwmg}\left[\sum_{l=1}^{n} \alpha^{l}_{iwmg} c^{\rho}_{iwmg,l} + \alpha^{h}_{iwmg} d^{\rho}_{iwmg}\right]^{(1-\rho)/\rho} c^{\rho-1}_{iwmg,l} - \lambda p_l = 0 \quad \forall l \tag{13}$$

$$(\lambda) \quad M_{iwmg} - r_i d_{iwmg} - \sum_{l=1}^{n} p_l c_{iwmg,l} - \kappa_{iwm} = 0 \tag{14}$$

$\frac{\partial U}{\partial c_l} > 0$ and $p_l > 0 \Rightarrow \lambda > 0$. Likewise, $\frac{\partial U}{\partial d} > 0$ and $r > 0 \Rightarrow \lambda > 0$. Using marginal rate of substitution between *d* and *c*:

$$c_{iwmg,l} = \left(\frac{\alpha_{iwmg}^{h}}{\alpha_{iwmg}^{l}} \frac{p_l}{r_i} \right)^{1/(\rho-1)} d_{iwmg} \tag{15}$$

Since $\rho = \frac{\sigma - 1}{\sigma}$, Equation (15) can be re-written as follows:

$$c_{iwmg,l} = \left(\frac{\alpha_{iwmg}^{l}}{\alpha_{iwmg}^{h}} \frac{r_i}{p_l} \right)^{\sigma} d_{iwmg} \tag{16}$$

I can write the associated demand function for dwellings in terms of relevant prices as:

$$d_{iwmg} = \left(\frac{\alpha_{iwmg}^{h}}{r_i} \right)^{\sigma} \frac{M_{iwmg} - \kappa_{iwm}}{\left(\alpha_{iwmg}^{h}\right)^{\sigma} r_i^{1-\sigma} + \sum_{l=1}^{n} \left(\alpha_{iwmg}^{l}\right)^{\sigma} p_l^{1-\sigma}} \tag{17}$$

Hence, using the above equation, I can write the associated demand function for consumption goods for each sector as in the following equation:

$$c_{iwmg,l} = \left(\frac{\alpha_{iwmg}^{l}}{p_l} \right)^{\sigma} \frac{M_{iwmg} - \kappa_{iwm}}{\left(\alpha_{iwmg}^{h}\right)^{\sigma} r_i^{1-\sigma} + \sum_{l=1}^{n} \left(\alpha_{iwmg}^{l}\right)^{\sigma} p_l^{1-\sigma}} \qquad \forall l \tag{18}$$

Hence, the corresponding indirect utility function becomes:

$$V_{iwmg}\left(d, c\right) = \left(M_{iwmg} - \kappa_{iwm}\right) \left[\left(\alpha_{iwmg}^{h}\right)^{\sigma} r_i^{1-\sigma} + \sum_{k=1}^{n} \left(\alpha_{iwmg}^{k}\right)^{\sigma} p_k^{1-\sigma} \right]^{1/(\sigma-1)} \tag{19}$$

Finally, total demand for housing at each location and consumption goods can be written as in the following equations:

$$D_i = \sum_{w} \sum_{m} \sum_{g} d_{iwmg} \qquad \forall i \tag{20}$$

$$C_l = \sum_i \sum_w \sum_m \sum_g c_{iwmg,l} \qquad \forall l \tag{21}$$

Now that we are interested in the impact of travel cost on household's problem, an initial approach would be to investigate the comparative statics of the model. The impact of an increase in travel cost:

$$\frac{\partial d_i^*}{\partial \kappa} = -\left(\frac{\alpha_{iwmg}^h}{r_i}\right)^\sigma \left[\left(\alpha_{iwmg}^h\right)^\sigma r_i^{1-\sigma} + \sum_{l=1}^n \left(\alpha_{iwmg}^l\right)^\sigma p_l^{1-\sigma}\right]^{-1} < 0 \tag{22}$$

$$\frac{\partial c_l^*}{\partial \kappa} = -\left(\frac{\alpha_{iwmg}^l}{p_l}\right)^\sigma \left[\left(\alpha_{iwmg}^h\right)^\sigma r_i^{1-\sigma} + \sum_{l=1}^n \left(\alpha_{iwmg}^l\right)^\sigma p_l^{1-\sigma}\right]^{-1} < 0 \tag{23}$$

$$\frac{\partial V^*}{\partial \kappa} = -\left[\left(\alpha_{iwmg}^h\right)^\sigma r_i^{1-\sigma} + \sum_{k=1}^n \left(\alpha_{iwmg}^k\right)^\sigma p_k^{1-\sigma}\right]^{1/(\sigma-1)} < 0 \tag{24}$$

The main driver affecting total travel cost is the travel distance. In monocentric cities, it is acknowledged that housing prices decrease as distance to city centre increases[8]. This is also applicable to cities with different attraction centres. For comparative statics analysis only, I assume that total travel cost is a linearly increasing function of distance ω_{iw}:

$$\kappa_{iw} = \eta \omega_{iw} \tag{25}$$

Housing prices decrease as distance to attraction zone increases, $\frac{dr}{d\omega} < 0$. So, the distance effect on the household utility:

$$\begin{aligned}\frac{\partial V^*}{\partial \omega} &= \left[\left(\alpha_{iwmg}^h\right)^\sigma r_i^{1-\sigma} + \sum_{k=1}^n \left(\alpha_{iwmg}^k\right)^\sigma p_k^{1-\sigma}\right]^{1/(\sigma-1)} \\ &\qquad \left[-\eta - \left(\frac{\alpha_{iwmg}^h}{r_i}\right)^\sigma \frac{\left(M_{iwmg} - \eta\omega_{iw}\right)}{\left(\alpha_{iwmg}^h\right)^\sigma r_i^{1-\sigma} + \sum_{k=1}^n \left(\alpha_{iwmg}^k\right)^\sigma p_k^{1-\sigma}} \frac{dr}{d\omega}\right] \\ &= \lambda\left(-\eta - d^* \frac{dr}{d\omega}\right)\end{aligned} \tag{26}$$

---

[8] See Brueckner (2011) for a further discussion on real estate prices and distance to the city centre.

So, the negative impact of distance decrease is compensated by an increase in housing utility to some extent. This explains the trade-off between housing expenditures and travel costs.

2.3.3 Residential Location and Travel Mode Choices of Households

The probability of choosing a residential location and associated travel mode for any household is calculated, first by redefining household utility function in compliance with discrete choice theory. This requires adding an idiosyncratic component associated with the agent heterogeneity:

$$U_{iwmg}\left(d,c\right)=\underbrace{\left[\sum_{k=1}^{n}\alpha_{iwmg}^{k}c_{iwmg,k}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right]^{1/\rho}+\Psi_{i}-\gamma_{iwmg}\tau_{iwm}}_{V_{iwmg}}+\varepsilon_{iwmg} \tag{27}$$

Proposition: Residential location and travel mode choice probability can be calculated using the following equation.

$$P_{w,g}\left(i,m\right)=\frac{e^{V_{iwmg}}}{\sum_{j}\sum_{m'}e^{V_{jwm'g}}}=\frac{\exp\left(\left[\sum_{l=1}^{n}\alpha_{iwmg}^{l}c_{iwmg,l}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right]^{1/\rho}+\Psi_{i}-\gamma_{iwmg}\tau_{iwm}\right)}{\sum_{j}\sum_{m'}\exp\left(\left[\sum_{l=1}^{n}\alpha_{jwm'g}^{l}c_{jwm'g,l}^{\rho}+\alpha_{jwm'g}^{h}d_{jwm'g}^{\rho}\right]^{1/\rho}+\Psi_{j}-\gamma_{jwm'g}\tau_{jwm'}\right)} \tag{28}$$

Proof: See Appendix E and Appendix F.

Therefore, a household (with a certain working location and skill level) selects certain residential location and transport mode for commuting among alternatives based on associated probabilities of these alternatives. It is important to note that this approach does not propose to select the alternative with the highest probability but identifies "market shares" of alternatives, which I explain below in details.

For each type of household, Equation (28) then can be used to calculate the total number of households choosing a specific residential location and the associated commuting mode. Assume that the number of households with skill level g and working at location w is exogenously given and $N\left(w,g\right)$. Then, the number of households for each location i using commuting mode m would be:

$$N_{i,m}\left(w,g\right)=P_{w,g}\left(i,m\right)\cdot N\left(w,g\right)$$
$$=\frac{\exp\left(\left[\sum_{l=1}^{n}\alpha_{iwmg}^{l}c_{iwmg,l}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right]^{1/\rho}+\Psi_{i}-\gamma_{iwmg}\tau_{iwm}\right)}{\sum_{j}\sum_{m'}\exp\left(\left[\sum_{l=1}^{n}\alpha_{jwm'g}^{l}c_{jwm'g,l}^{\rho}+\alpha_{jwm'g}^{h}d_{jwm'g}^{\rho}\right]^{1/\rho}+\Psi_{j}-\gamma_{jwm'g}\tau_{jwm'}\right)}N\left(w,g\right) \quad (29)$$

So, the total number of households choosing to live at a specific location *i*, which can be thought of as the aggregate demand for houses at a location, is:

$$N_i=\sum_{m}\sum_{w}\sum_{g}N_{i,m}\left(w,g\right) \quad \forall i \quad (30)$$

It is obvious that aggregating all household numbers obtained from the above equation will be equal to the total number of households living in a study area (a city in our case).

$$N=\sum_{i}N_i \quad (31)$$

2.3.4 Firms

In its most general form where there is multi-industry structure, production function of each industry is assumed to exhibit a constant-elasticity-of-substitution (CES) form. To produce goods in the respective industries, producers use composite labour, which exhibits a CES function of two categories: (i) non-qualified (or unskilled) and (ii) qualified (or skilled), and capital. They also use intermediate goods that are obtained as inputs from the other industries. The difference between the value of the output and total values of the intermediate goods used in production is attributed to the "value-added (VA)" of the industry. Following Cardenete et al. (2012) the production function is defined in two levels, where well-known Leontief production function is used in the upper level to produce the output y_l:

$$y_l=\min\left(\frac{VA_l}{v_l},\frac{y_{1l}}{a_{1l}},\frac{y_{2l}}{a_{2l}},\dots,\frac{y_{nl}}{a_{nl}}\right) \quad \forall l \quad (32)$$

where *VA* is the value-added, *v* is the quantity of value-added needed for the one-unit production of output, y_{kl} is the quantity of intermediate good *k* needed for the one-unit production of output y_l and a_{kl} is the input-output coefficient.

CES production function is used in the lower level to bring together capital and composite labour to produce the value added in each sector *l*:

$$VA_l = v_l \cdot y_l = \phi_l \left(\beta_l K_l^{\frac{(\sigma-1)}{\sigma}} + \left(1-\beta_l\right) L_l^{\frac{(\sigma-1)}{\sigma}} \right)^{\frac{\sigma}{(\sigma-1)}} \tag{33}$$

where ϕ denotes the total factor productivity, β denotes the CES production function factor share coefficient for the capital, *L* denotes composite labour as the factor input, *K* denotes capital as the factor input and σ is the elasticity of substitution between labour and capital.

Labour is assumed to be supplied from two groups, skilled and unskilled. Composite labour is defined as a CES function of skilled and unskilled labour|:

$$L_l = \left(\beta_l^L LS_l^{\frac{\left(\sigma^L-1\right)}{\sigma^L}} + \left(1-\beta_l^L\right) LU_l^{\frac{\left(\sigma^L-1\right)}{\sigma^L}} \right)^{\frac{\sigma^L}{\left(\sigma^L-1\right)}} \tag{34}$$

where β_l^L is the share of skilled labour for industry *l*, σ^L is the elasticity of substitution between skilled labour and unskilled labour, *LS* and *LU* denote demands for skilled labour and unskilled labour respectively. Therefore, one can re-write industrial value added in terms of labour types as follows:

$$VA_l = v_l \cdot y_l = \phi_l \left(\beta_l K_l^{\frac{(\sigma-1)}{\sigma}} + \left(1-\beta_l\right) \left(\beta_l^L LS_l^{\frac{\left(\sigma^L-1\right)}{\sigma^L}} + \left(1-\beta_l^L\right) LU_l^{\frac{\left(\sigma^L-1\right)}{\sigma^L}} \right)^{\frac{\sigma^L(\sigma-1)}{\left(\sigma^L-1\right)\sigma}} \right)^{\frac{\sigma}{(\sigma-1)}} \tag{35}$$

The motivation of producers is to minimise their costs while producing some level of goods. Therefore, the producers in an industry solve a cost minimisation problem. It should be noted that, from here, indices denoting industry types are dropped from equations for the sake of simplicity in notations.

Deriving the first-order conditions with respect to the production factors and the Lagrange multiplier and using these equalities lead to following equations for factor demands in production in terms of factor prices and skilled labour demand *LS*:

$$LU = LS\left[\frac{w_S\left(1-\beta^L\right)}{w_U\beta^L}\right]^{\sigma^L} \tag{36}$$

$$K = LS\left(\frac{w_S}{\delta}\right)^{\sigma}\left(\frac{\beta}{(1-\beta)}\right)^{\sigma}\beta^{L\,\frac{\sigma^L(1-\sigma)}{\left(\sigma^L-1\right)}}\left[1+\left(\frac{1-\beta^L}{\beta^L}\right)^{\sigma^L}\left(\frac{w_S}{w_U}\right)^{\left(\sigma^L-1\right)}\right]^{\frac{\sigma^L-\sigma}{\left(\sigma^L-1\right)}} \tag{37}$$

Therefore, above equations and the definition of the value-added term can be used to derive factor demand functions.

$$\begin{gathered}LS = \frac{VA}{\phi}\left[(1-\beta)\delta\right]^{\sigma}\left(\beta^L\left[1+\left(\frac{1-\beta^L}{\beta^L}\right)^{\sigma^L}\left(\frac{w_S}{w_U}\right)^{\left(\sigma^L-1\right)}\right]\right)^{\frac{\sigma^L}{\left(1-\sigma^L\right)}}\\ \left(\left[1+\left(\frac{1-\beta^L}{\beta^L}\right)^{\sigma^L}\left(\frac{w_S}{w_U}\right)^{\left(\sigma^L-1\right)}\right]^{\frac{(1-\sigma)}{\left(\sigma^L-1\right)}}\left(\beta^L\right)^{(1-\sigma)}\beta^{\sigma}\left(w_S\right)^{(\sigma-1)}+(1-\beta)^{\sigma}\delta^{(\sigma-1)}\right)^{\frac{\sigma}{(1-\sigma)}}\end{gathered} \tag{38}$$

$$\begin{gathered}LU = \frac{VA}{\phi}\left[(1-\beta)\delta\right]^{\sigma}\left(\left(1-\beta^L\right)\left[1+\left(\frac{\beta^L}{1-\beta^L}\right)^{\sigma^L}\left(\frac{w_U}{w_S}\right)^{\left(\sigma^L-1\right)}\right]\right)^{\frac{\sigma^L}{\left(1-\sigma^L\right)}}\\ \left(\left[1+\left(\frac{1-\beta^L}{\beta^L}\right)^{\sigma^L}\left(\frac{w_S}{w_U}\right)^{\left(\sigma^L-1\right)}\right]^{\frac{(1-\sigma)}{\left(\sigma^L-1\right)}}\left(\beta^L\right)^{(1-\sigma)}\beta^{\sigma}\left(w_S\right)^{(\sigma-1)}+(1-\beta)^{\sigma}\delta^{(\sigma-1)}\right)^{\frac{\sigma}{(1-\sigma)}}\end{gathered} \tag{39}$$

$$\begin{gathered}K = \frac{VA}{\phi}\left(\beta w_S\right)^{\sigma}\left(\left(\beta^L\right)^{\sigma^L}\left[1+\left(\frac{1-\beta^L}{\beta^L}\right)^{\sigma^L}\left(\frac{w_S}{w_U}\right)^{\left(\sigma^L-1\right)}\right]\right)^{\frac{\sigma}{\left(1-\sigma^L\right)}}\\ \left(\left[1+\left(\frac{1-\beta^L}{\beta^L}\right)^{\sigma^L}\left(\frac{w_S}{w_U}\right)^{\left(\sigma^L-1\right)}\right]^{\frac{(1-\sigma)}{\left(\sigma^L-1\right)}}\left(\beta^L\right)^{(1-\sigma)}\beta^{\sigma}\left(w_S\right)^{(\sigma-1)}+(1-\beta)^{\sigma}\delta^{(\sigma-1)}\right)^{\frac{\sigma}{(1-\sigma)}}\end{gathered} \tag{40}$$

Hence, I can write the cost function in terms of factor prices and the value-added as

$$C_{VA}\left(\delta,w_S,w_U\right)=\frac{VA}{\phi}\left\{\begin{array}{l}\left[\left[\left(1-\beta\right)\delta\right]^{\sigma}w_Sw_UH^{\frac{1}{\left(1-\sigma^L\right)}}+\delta\left[\beta w_Sw_U\right]^{\sigma}H^{\frac{\sigma}{\left(1-\sigma^L\right)}}\right]\\ \left[H^{\frac{(\sigma-1)}{\left(1-\sigma^L\right)}}\left(\beta^L\right)^{\frac{(\sigma-1)}{\left(\sigma^L-1\right)}}\beta^{\sigma}\left(w_Sw_U\right)^{(\sigma-1)}+\left(1-\beta\right)^{\sigma}\delta^{(\sigma-1)}\right]^{\frac{\sigma}{(1-\sigma)}}\end{array}\right\} \tag{41}$$

where $H=\left[\left(\beta^L\right)^{\sigma^L}\left(w_U\right)^{\left(\sigma^L-1\right)}+\left(1-\beta^L\right)^{\sigma^L}\left(w_S\right)^{\left(\sigma^L-1\right)}\right]$.

Price for value-added becomes:

$$p_{VA}\left(\delta,w_S,w_U\right)=\frac{1}{\phi}\left\{\begin{array}{l}\left[\left[\left(1-\beta\right)\delta\right]^{\sigma}w_Sw_UH^{\frac{1}{\left(1-\sigma^L\right)}}+\delta\left[\beta w_Sw_U\right]^{\sigma}H^{\frac{\sigma}{\left(1-\sigma^L\right)}}\right]\\ \left[H^{\frac{(\sigma-1)}{\left(1-\sigma^L\right)}}\left(\beta^L\right)^{\frac{(\sigma-1)}{\left(\sigma^L-1\right)}}\beta^{\sigma}\left(w_Sw_U\right)^{(\sigma-1)}+\left(1-\beta\right)^{\sigma}\delta^{(\sigma-1)}\right]^{\frac{\sigma}{(1-\sigma)}}\end{array}\right\} \tag{42}$$

Using the above equation and the total cost of intermediate goods, we can write the cost function of the total output (for each industry) as follows:

$$C^l\left(\delta,w_S,w_U\right)=p_{VA}^l\left(\delta,w_S,w_U\right)\cdot VA_l+\sum_{k=1}^{n}p_ky_{kl}\qquad\forall l \tag{43}$$

Using the "zero profit" condition, the definition of value-added in Equation (33) and the definition of input-output coefficients, $y_{kl}=a_{kl}y_l$, we can write the cost function as follows:

$$p_ly_l=p_{VA}^l\left(\delta,w_S,w_U\right)v_ly_l+\sum_{k=1}^{n}p_ka_{kl}y_l\qquad\forall l \tag{44}$$

Then cancelling common terms in both sides of the equation leads to the output price for an industry:

$$p_l=p_{VA}^l\left(\delta,w_S,w_U\right)v_l+\sum_{k=1}^{n}p_ka_{kl}\qquad\forall l \tag{45}$$

2.3.5 Equilibrium

The set of equations defining equilibrium of the CGE model can be grouped in five blocks: (i) household decisions on residential locations (in other words, household location choice model), (ii) household decisions on consumption demand, (iii) firms' decision on production, (iv) travel model and (v) market clearing conditions. Understanding linkages among these blocks is critical to understand how the integrated model behaves. This requires a brief explanation on variable/parameter exchange among models. As shown in Figure 2.3, household location choice model needs demand figures for consumption goods and housing from the economic model while travel time values are taken from the travel model. The number of households residing at specific locations is important, both for scaling goods consumption and forming OD matrix, which is fundamental to the travel model.

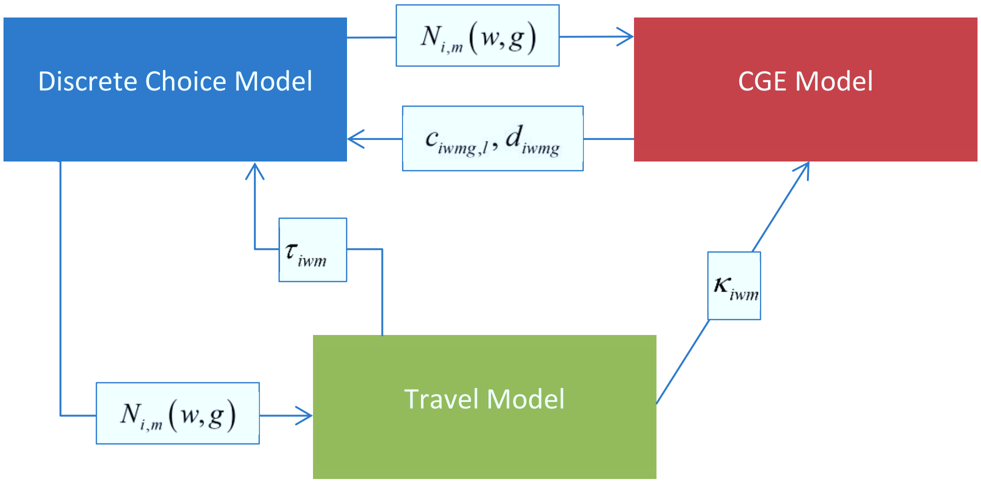


Figure 2.3 Exchanging variable/parameters among models

2.3.5.1 Household decisions on residential location and commuting mode

1) The number of households residing at a specific location and using a specific commuting mode is calculated by using the following equation. As there is no change in household composition (owing to migration or natural population changes), it is assumed that households do change their jobs and employment locations are fixed. $N(w,g)$ (number of households working in location w with skill level g) remains unchanged, so it is treated as an exogeneous parameter in the model.

$$N_{i,m}\left(w,g\right)=\frac{\exp\left(\left[\sum_{l=1}^{n}\alpha_{iwmg}^{l}c_{iwmg,l}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right]^{1/\rho}+\Psi_{i}-\gamma_{iwmg}\tau_{iwm}\right)}{\sum_{j}\sum_{m'}\exp\left(\left[\sum_{l=1}^{n}\alpha_{jwm'g}^{l}c_{jwm'g,l}^{\rho}+\alpha_{jwm'g}^{h}d_{jwm'g}^{\rho}\right]^{1/\rho}+\Psi_{j}-\gamma_{jwm'g}\tau_{jwm'}\right)}N\left(w,g\right)$$

$\forall i,m$

2.3.5.2 Household decisions on consumption

1) Disposable income of a household:

$$M_{iwmg}=w_{g}+\delta e_{iwmg}^{K}+\sum_{i'}r_{i'}e_{iwmg}^{H}\left(i'\right)$$

2) Household's demand for consumption goods:

$$c_{iwmg,l}=\left(\frac{\alpha_{iwmg}^{l}}{p_{l}}\right)^{\sigma}\frac{M_{iwmg}-\kappa_{iwm}}{\left(\alpha_{iwmg}^{h}\right)^{\sigma}r_{i}^{1-\sigma}+\sum_{l=1}^{n}\left(\alpha_{iwmg}^{l}\right)^{\sigma}p_{l}^{1-\sigma}}\qquad\forall l$$

3) Total demand for consumption goods for each sector is calculated using aggregate consumption of households:

$$c_{l}=\sum_{i}\sum_{w}\sum_{m}\sum_{g}N_{i,m}\left(w,g\right)\cdot c_{iwmg,l}\qquad\forall l$$

4) Any household decides on floor space of housing at a predefined location:

$$d_{iwmg}=\left[\frac{\alpha_{iwmg}^{h}}{r_{i}}\right]^{\sigma}\frac{M_{iwmg}-\kappa_{iwm}}{\left(\alpha_{iwmg}^{h}\right)^{\sigma}r_{i}^{1-\sigma}+\sum_{l=1}^{n}\left(\alpha_{iwmg}^{l}\right)^{\sigma}p_{l}^{1-\sigma}}$$

2.3.5.3 Firms decisions on production

1) Price index for optimal value-added used for each sector:

$$p_{VA}^{l}\left(\delta,w_{S},w_{U}\right)=\frac{1}{\phi_{l}}\left\{\begin{array}{l}\left[\left[\left(1-\beta_{l}\right)\delta\right]^{\sigma_{l}}w_{S}w_{U}H_{l}^{\frac{1}{\left(1-\sigma_{l}^{L}\right)}}+\delta\left[\beta_{l}w_{S}w_{U}\right]^{\sigma_{l}}H_{l}^{\frac{\sigma_{l}}{\left(1-\sigma_{l}^{L}\right)}}\right]\\ \left[H_{l}^{\frac{\left(\sigma_{l}-1\right)}{\left(1-\sigma_{l}^{L}\right)}}\left(\beta_{l}^{L}\right)^{\frac{\left(\sigma_{l}-1\right)}{\left(\sigma_{l}^{L}-1\right)}}\beta_{l}^{\sigma_{l}}\left(w_{S}w_{U}\right)^{\left(\sigma_{l}-1\right)}+\left(1-\beta_{l}\right)^{\sigma_{l}}\delta^{\left(\sigma_{l}-1\right)}\right]^{\frac{\sigma_{l}}{\left(1-\sigma_{l}\right)}}\end{array}\right\}$$

$$\forall l \text{ and } H_l = \left[\left(\beta_l^L\right)^{\sigma_l^L} \left(w_U\right)^{\left(\sigma_l^L-1\right)} + \left(1-\beta_l^L\right)^{\sigma_l^L} \left(w_S\right)^{\left(\sigma_l^L-1\right)} \right].$$

2) Goods prices for each sector obtained from the zero-profit condition for firms:

$$p_l = p_{VA}^l\left(\delta, w_S, w_U\right) v_l + \sum_{k=1}^{n} p_k a_{kl} \qquad \forall l$$

3) Technical coefficient for capital in an industry:

$$b_K^l = \frac{K_l}{VA_l} = \frac{\left(\beta_l w_S\right)^{\sigma}}{\phi_l} \left(\left(\beta_l^L\right)^{\sigma_l^L} \left[1+\left(\frac{1-\beta_l^L}{\beta_l^L}\right)^{\sigma^L} \left(\frac{w_S}{w_U}\right)^{\left(\sigma_l^L-1\right)} \right] \right)^{\frac{\sigma_l}{\left(1-\sigma_l^L\right)}}$$

$$\left(\left[1+\left(\frac{1-\beta_l^L}{\beta_l^L}\right)^{\sigma_l^L} \left(\frac{w_S}{w_U}\right)^{\left(\sigma_l^L-1\right)} \right]^{\frac{(1-\sigma_l)}{\left(\sigma_l^L-1\right)}} \left(\beta_l^L\right)^{(1-\sigma_l)} \beta_l^{\sigma_l} \left(w_S\right)^{(\sigma_l-1)} + \left(1-\beta_l\right)^{\sigma_l} \delta^{(\sigma_l-1)} \right)^{\frac{\sigma_l}{(1-\sigma_l)}}$$

$\forall l$

4) Technical coefficient for skilled labour in an industry:

$$b_{LS}^l = \frac{LS_l}{VA_l} = \frac{\left[\left(1-\beta_l\right)\delta\right]^{\sigma_l}}{\phi_l} \left(\beta_l^L \left[1+\left(\frac{1-\beta_l^L}{\beta_l^L}\right)^{\sigma_l^L} \left(\frac{w_S}{w_U}\right)^{\left(\sigma_l^L-1\right)} \right] \right)^{\frac{\sigma_l^L}{\left(1-\sigma_l^L\right)}}$$

$$\left(\left[1+\left(\frac{1-\beta_l^L}{\beta_l^L}\right)^{\sigma_l^L} \left(\frac{w_S}{w_U}\right)^{\left(\sigma_l^L-1\right)} \right]^{\frac{(1-\sigma_l)}{\left(\sigma_l^L-1\right)}} \left(\beta_l^L\right)^{(1-\sigma_l)} \beta_l^{\sigma_l} \left(w_S\right)^{(\sigma_l-1)} + \left(1-\beta_l\right)^{\sigma_l} \delta^{(\sigma_l-1)} \right)^{\frac{\sigma_l}{(1-\sigma_l)}}$$

$\forall l$

5) Technical coefficient for unskilled labour in an industry:

$$b_{LU}^l = \frac{LU_l}{VA_l} = \frac{\left[\left(1-\beta_l\right)\delta\right]^{\sigma_l}}{\phi_l} \left(\left(1-\beta_l^L\right) \left[1+\left(\frac{\beta_l^L}{1-\beta_l^L}\right)^{\sigma_l^L} \left(\frac{w_U}{w_S}\right)^{\left(\sigma_l^L-1\right)} \right] \right)^{\frac{\sigma_l^L}{\left(1-\sigma_l^L\right)}}$$

$$\left(\left[1+\left(\frac{1-\beta_l^L}{\beta_l^L}\right)^{\sigma_l^L} \left(\frac{w_S}{w_U}\right)^{\left(\sigma_l^L-1\right)} \right]^{\frac{(1-\sigma_l)}{\left(\sigma_l^L-1\right)}} \left(\beta_l^L\right)^{(1-\sigma_l)} \beta_l^{\sigma_l} \left(w_S\right)^{(\sigma_l-1)} + \left(1-\beta_l\right)^{\sigma_l} \delta^{(\sigma_l-1)} \right)^{\frac{\sigma_l}{(1-\sigma_l)}}$$

$\forall l$

6) Total industrial demand on skilled labour as a factor for production:

$$LS = \sum_{l=1}^{n} LS_l = \sum_{l=1}^{n} b_{LS}^l v_l y_l$$

7) Total industrial demand on unskilled labour as a factor for production:

$$LU=\sum_{l=1}^{n}LU_l=\sum_{l=1}^{n}b_{LU}^{l}v_l y_l$$

8) Total industrial demand on capital as a factor for production:

$$K=\sum_{l=1}^{n}K_l=\sum_{l=1}^{n}b_{K}^{l}v_l y_l$$

2.3.5.4 Travel model (for private transport)

1) Sum of traffic flows on different paths for specific journeys from *i* to *w* equals to travel demand from *i* to *w*:

$$\sum_{path}f_{path}^{iw}=q_{iw}\left(f_{path}^{iw}\geq 0\right)$$

2) Sum of all traffic flows using a link equals to traffic flow on this link:

$$x_a=\sum_{i}\sum_{w}\sum_{path}f_{path}^{iw}\cdot\Delta_{a,path}^{iw}$$

3) Travel time on a link:

$$t_a=\mathrm{A}_a+\mathrm{B}_a\left[\frac{x_a}{Q_a}\right]^4$$

4) Total travel time of a path from *i* to *w*:

$$t_{path}^{iw}=\sum_{a}t_a\cdot\Delta_{a,path}^{iw}$$

5) Wardrop's First Principle:

$$t_{path=1}^{iw}=\sum_{path}\frac{t_{path}^{iw}}{\pi\left(i,w\right)}=\tau_{iwm='1'}$$

6) Total travel cost of a journey (private transport):

$$\kappa_{iwm='1'}=\left[C^f+\frac{\tau_{iwm='1'}}{\tau_{iwm='1'}^{f}}\frac{t_{100}^{f}}{t_{100}^{c}}\left(C^c-C^f\right)\right]\cdot D_{iw}\cdot p^f$$

2.3.5.5 Market clearing equations

1) Total production for goods would be equal to the sum of final consumption by households and consumption as intermediate goods in sectors[9]:

$$y_k = c_k + \sum_l a_{kl} y_l \qquad \forall k$$

2) Total factor utilisation of labour cannot exceed initial household endowments:

$$LS \le \sum_i \sum_w \sum_m N_{i,m}\left(w, g = 'S'\right) \cdot e^L_{iwmg='S'}$$

$$LU \le \sum_i \sum_w \sum_m N_{i,m}\left(w, g = 'U'\right) \cdot e^L_{iwmg='U'}$$

3) Total factor utilisation of capital cannot exceed initial household endowments:

$$K \le \sum_i \sum_w \sum_m \sum_g N_{i,m}\left(w, g\right) \cdot e^K_{iwmg}$$

4) Total housing demand of households cannot exceed housing capacity at each location:

$$\sum_w \sum_m \sum_g N_{i',m}\left(w, g\right) \cdot d_{i'wmg} \le \sum_i \sum_w \sum_m \sum_g e^H_{iwmg}\left(i'\right) \qquad \forall i'$$

5) Number of households commuting between nodes *i* and *w* using private transport equals to OD trip between these nodes:

$$\sum_g N_{i,m='1'}\left(w, g\right) = q_{iw}$$

2.4 Discussion

In the context of this study, in general, it was aimed to present a general modelling framework focusing on household decisions. The proposed model brings discrete choices of households (residential location and transport mode), macroeconomic general equilibrium and road traffic equilibrium together. This

---

[9] Transport is treated as an industry in market clearing equations and its consumption is added to the final output. Therefore, households expenditures on transport would be used for the activities of this sector.

integration allows us to make a more comprehensive assessment of transport policies. Using this modelling framework, it would be possible to evaluate wider economic impacts of policies while agent level information is not lost in aggregation. That’s to say, proposed modelling framework serves the purpose of choosing more equitable transport policies paying regard to disparities.

Data is extremely crucial. What types of data we need and how we should treat gathered data are explained in this study. It is likely that one would easily criticise the proposed model severely for its data-hungry nature. However, we should bear in mind that census studies provide plenty of information about households. In case of census data don’t include some of the required attributes; household surveys can be used to impute these attributes into the census.

CHAPTER 3

TESTING THE MODEL USING PSEUDO DATA

3.1 Introduction

Project appraisal is an important procedure to assess the feasibility of transport projects. This makes it critical to select right projects given the budget constraint of investments. However, recalling the discussion about the capability of appraisal methods in the Introduction of the Thesis, standard cost and benefit appraisal methods do not fully address economic impacts of transport investments (Graham, 2007). Integrating micro-simulation models, which perform well in modelling behaviours of economic agents using micro-level data, with general equilibrium models, on the other hand, is a promising approach in transport appraisal.

One of the earlier examples of integrated models that were used in transport project appraisal is Kim et al. (2004). The authors propose an integrated framework with a dynamic computable general equilibrium (CGE) model coupled with a transport model, which measures accessibility changes, to evaluate highway projects in terms of economic growth and regional disparity in South Korea. In this study, among the grid-type highway network with seven South-North highways and nine East-West highways, four highways are selected to be assessed in terms of economic measures (benefit-cost ratios and GDP, price and export multipliers) and distributional effects (wage and population) using the proposed integrated model.

Knaap and Oosterhaven (2011) use a CGE model (RAEM) of Knaap and Oosterhaven (2000) to evaluate impacts of six different rail connection alternatives for linking Groningen City and Schiphol Airport along with the reference scenario. They evaluate these infrastructure projects in terms of their regional employment effects and national output, price and welfare effects. Scenario analyses of this study show that all the projects would lead to varying levels of decrease in consumer price index, and eventually, increase in national output. The study shows that, among the alternatives, magnetic levitation track with stops at all five intermediate stations between Groningen City and Schiphol Airport (scenario MZM) would lead to a spatial shift of 8,100 jobs.

Anas and Hiramatsu (2012) use a spatial CGE model (RELU) detailed in Anas and Liu (2007) to understand impacts of an increase in gasoline price on urban economy. This model in the study is calibrated for the Chicago MSA, which is divided into 5 rings covering 15 zones. They integrate this CGE model with a transport model (TRAN) modelling households' discrete choices on travel mode and route choice. Using this framework, they simulate the gasoline price increase in the Chicago MSA from a base value of 1.6 USD in 2000 to 2.45 USD in 2007 alongside with 2.7 per cent decrease in technological fuel intensity (TFI) and changes in car acquisition costs. RELU-TRAN framework is used to evaluate impacts of cordon tolling to be implemented in the Chicago MSA in terms of travel, housing and labour markets, to compare Pigouvian tolling of traffic congestion and gasoline tax policies in terms of locations of jobs and residences and to evaluate the effects of planned public transport investments in Paris (Anas, 2013a).

Hensher et al. (2012) integrate a transport and location choice modelling system (TRESIS) with a spatial CGE model (SGEM) to evaluate impacts of North-West Rail Link project in Sydney, Australia. TRESIS models household decisions on residential location, housing type, working location, vehicle ownership and travel mode. Origin-Destination (OD) matrix of trips is also estimated using TRESIS model. In SGEM, each zone in a city is treated as an economy and trade (employment and income flow) can take place among these zones. In this study, transport improvements of North-West Rail Link project are used by TRESIS to decide on household housing and working locations, and travel preferences. The output of the microsimulation model, which clearly identifies the potential employment redistribution within Sydney Metropolitan Area, is used in CGE model to model agglomeration and wider economic benefit of the project.

Turning to the model I propose in this Thesis; equilibrium values are calculated without any iteration looking for convergence owing to the integration procedure where models are running simultaneously. In this Chapter, I test the proposed integrated model using a pseudo data set of a representative urban unit with four districts. Households are differentiated according to their residential location, working location, preferred commuting mode and social status. In the scenario analysis, I evaluate a set of alternative transport policies (i.e. capacity increase in private transport, public transport improvement, cordon pricing) and analyse the impacts of such policies on a set of parameters including household locational distribution, households' demand on consumption goods and housing, and housing prices observed.

The organisation of this Chapter is as follows.

I study the model and the first set of scenario analyses in Section 3.2. In order to capture the relevance of representing the heterogeneity of households, I introduce the elements of heterogeneity (location categories, travel mode, socio/economic groups) in sequence and discuss the results under a specific scenario (a new private transport link between two districts of a city). Section 3.3 presents two other simulations under the full heterogeneity set, namely introduction of a (substitute) public transport system and a cordon pricing policy. All scenarios are carried out utilizing a synthetic data for a city with four residential/working districts. Section 3.4 briefly discusses about findings.

3.2 Model Specifications and Scenario Analysis

Recalling modelling approach in Chapter 2, this study constructs an urban CGE model with heterogeneous households and firms. It is a residential location choice model in a general equilibrium framework.

Households earn income by renting production factors (capital and labour) to the firms and housing units to other households. Firms carry out production activities and distribute factor incomes. Households consume a composite good and housing. The CGE model determines prices and quantities of these consumptions simultaneously.

Transport is included in household utility problem as a unit causing negative utility due to spent time on journeys[10]. Transport expenditure is considered in budget

---

[10] See Anas and Liu (2007) and Anas and Hiramatsu (2013) for constant utility effects of choices.

constraints of households and contributes to the final output of the economy. The transport model calculates private transport travel times (and travel costs) between the specified nodes in the city. It considers the impact of congestion on travel times.

Recalling the discussion on fixed population pool in Chapter 2, households decide on housing locations and associated transport modes for commuting. Producers are assumed to be fixed at their operational locations as well. They are not exposed to any transport cost.

3.2.1 Model Specifications

Households maximise their utilities in accordance with the following utility function and household budget constraint:

$$U_{iwmg}\left(d,c\right)=\left(\alpha_{iwmg}c_{iwmg}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right)^{1/\rho}-\gamma_{iwmg}\tau_{iwm} \tag{1}$$

$$-M_{iwmg}+r_i d_{iwmg}+pc_{iwmg}+\kappa_{iwm}\leq 0 \tag{2}$$

Here, *d* is the consumption on housing (floor space), *c* is the quantity of consumed goods, $\rho=(\sigma-1)/\sigma$ and σ is the elasticity of substitution between the housing and the consumption good, α stands for CES coefficients of household utilities, γ is the coefficient for travelling disutility varying by household type and τ is travel time. Consuming one type of consumption good and housing units would increase household utility while travelling causes disutility. In household budget constraint, *M* is household income, *r* is the rental rate of housing units, *p* is the price of the consumption good and *κ* is transport cost.

The one-sector of the model representing aggregate economic activity is assumed to exhibit a constant-elasticity-of-substitution (CES) form using one type of labour and capital. Producers solve the following cost minimisation problem for a level of production output:

$$\begin{aligned}&\text{Min } \delta K+wL\\&\quad s.t.\\&y=\phi\left(\beta K^{\rho}+(1-\beta)L^{\rho}\right)^{1/\rho}\end{aligned} \tag{3}$$

where δ is the rental rate of the capital used for the production and *w* is the wage rate paid to the employees. Therefore, factor demand functions can be interpreted in terms of production output as in the following equations:

$$L = \frac{y}{\phi}\left[\beta^{\sigma}\delta^{1-\sigma} + \left(1-\beta\right)^{\sigma} w^{1-\sigma}\right]^{\frac{\sigma}{1-\sigma}} \left(1-\beta\right)^{\sigma} w^{-\sigma} \tag{4}$$

$$K = \frac{y}{\phi}\left[\beta^{\sigma}\delta^{1-\sigma} + \left(1-\beta\right)^{\sigma} w^{1-\sigma}\right]^{\frac{\sigma}{1-\sigma}} \beta^{\sigma}\delta^{-\sigma} \tag{5}$$

Using factor demand functions, the cost function of producers in terms of factor prices can be written as in the following form:

$$C\left(\delta, w\right) = \delta K + wL = \left[\beta^{\sigma}\delta^{1-\sigma} + \left(1-\beta\right)^{\sigma} w^{1-\sigma}\right]^{\frac{1}{1-\sigma}} \frac{y}{\phi} \tag{6}$$

Thus, using the "zero profit" condition for producers, output price in terms of factor prices becomes:

$$p\left(\delta, w\right) = \frac{\left[\beta^{\sigma}\delta^{1-\sigma} + \left(1-\beta\right)^{\sigma} w^{1-\sigma}\right]^{\frac{1}{1-\sigma}}}{\phi} \tag{7}$$

Transport costs $\left(\kappa_{iwm}\right)$ are added to total GDP of this one-sector economy. Therefore, market clearing conditions for production and housing imply that:

$$y = \sum_{i}\sum_{w}\sum_{m}\sum_{g} N_{i,m}\left(w, g\right)\left(c_{iwmg} + \kappa_{iwm}\right) \tag{8}$$

$$K = \sum_{i}\sum_{w}\sum_{m}\sum_{g} N_{i,m}\left(w, g\right) \cdot e_{iwmg}^{K} \tag{9}$$

$$L = \sum_{i}\sum_{w}\sum_{m}\sum_{g} N_{i,m}\left(w, g\right) \cdot e_{iwmg}^{L} \tag{10}$$

$$\sum_{w}\sum_{m}\sum_{g} N_{i',m}\left(w, g\right) \cdot d_{i'wmg} = \sum_{i}\sum_{w}\sum_{m}\sum_{g} e_{iwmg}^{H}\left(i'\right) \quad \forall i' \tag{11}$$

where *N* is the number of household with relevant attributes and *e* stands for household endowments for business capital, labour and housing in floor space.

The probability of choosing a residential location and associated travel mode for any household is calculated as follows:

$$P_{w,g}\left(i,m\right)=\frac{e^{V_{iwmg}}}{\sum_{j}\sum_{m'}e^{V_{jwm'g}}}=\frac{\exp\left(\left(\alpha_{iwmg}c_{iwmg}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right)^{1/\rho}-\gamma_{iwmg}\tau_{iwm}\right)}{\sum_{j}\sum_{m'}\exp\left(\left(\alpha_{jwm'g}c_{jwm'g}^{\rho}+\alpha_{jwm'g}^{h}d_{jwm'g}^{\rho}\right)^{1/\rho}-\gamma_{jwm'g}\tau_{jwm'}\right)} \tag{12}$$

For each type of household, Equation (12) can be used to calculate the total number of households choosing a specific residential location and associated commuting mode. Assume that the number of households with skill level *g* and working at location *w* is exogenously given and *N(w,g)*. Then, the number of households for each location *i* using commuting mode *m* would be:

$$\begin{aligned}N_{i,m}\left(w,g\right)&=P_{w,g}\left(i,m\right)\cdot N\left(w,g\right)\\&=\frac{\exp\left(\left(\alpha_{iwmg}c_{iwmg}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right)^{1/\rho}-\gamma_{iwmg}\tau_{iwm}\right)}{\sum_{j}\sum_{m'}\exp\left(\left(\alpha_{jwm'g}c_{jwm'g}^{\rho}+\alpha_{jwm'g}^{h}d_{jwm'g}^{\rho}\right)^{1/\rho}-\gamma_{jwm'g}\tau_{jwm'}\right)}N\left(w,g\right)\end{aligned} \tag{13}$$

So, the total number of households choosing to live at a specific location *i*, which can be thought of as the aggregate demand for houses at a location, is:

$$N_{i}=\sum_{m}\sum_{w}\sum_{g}N_{i,m}\left(w,g\right)\qquad\forall i \tag{14}$$

It is obvious that aggregating all household numbers obtained from the above equation will be equal to the total number of households living in a study area (a city in this case).

$$N=\sum_{i}N_{i} \tag{15}$$

Travel model is a set of equations. It calculates private transport travel times between nodes using a convex and non-decreasing travel time function with respect to traffic flow. User equilibrium (UE) model based on Wardrop's (1952) First Principle where total travel time along an arc is a function of free flow travel time and additional time required due to increasing traffic density.

(1) Sum of traffic flows on different paths for specific journeys from *o* to *d* equals to travel demand from *o* to *d*:

$$\sum_p f_p^{od} = q_{od} \left(f_p^{od} \geq 0 \right) \tag{16}$$

where f_p^{od} is traffic flow on path *p* from *o* to *d* and q_{od} is travel demand from *o* to *d*.

(2) Sum of all traffic flows using a link equals to traffic flow on this link:

$$x_a = \sum_o \sum_d \sum_p f_p^{od} \cdot \Delta_{a,p}^{od} \tag{17}$$

where, x_a is traffic flow on the link *a* and $\Delta_{a,p}^{od}$ is link-path incidence parameter (1 if link *a* belongs to path *p* from *o* to *d*, 0 otherwise)

(3) Travel time on a link is calculated using a convex non-decreasing function:

$$t_a = \mathrm{A}_a + \mathrm{B}_a \left[\frac{x_a}{Q_a} \right]^4 \tag{18}$$

where, $t_a(x)$ is travel time on the link *a*, A_a is the time required to traverse link *a* under no traffic condition, B_a is traffic congestion coefficient for the link *a* and Q_a is the link capacity.

(4) The total travel time of a path from *o* to *d* equals to the sum of travel times of all links belonging to this path:

$$t_p^{od} = \sum_a t_a \cdot \Delta_{a,p}^{od} \tag{19}$$

(5) If a path is used for travelling from *o* to *d* travel time of this path will be equal to any path that is used for travelling from *o* to *d* (Wardrop's First Principle) where $\pi(o,d)$ is the number of alternative paths used for journeys from *o* to *d*:

$$t_{p=1}^{od} = \sum_p \frac{t_p^{od}}{\pi(o,d)} \tag{20}$$

3.2.2 Scenario I-1: Capacity Increase in Private Transportation (Model with location categories only)

I design a synthetic city for the prototype model described briefly above. This city has four different districts. One of these districts (District 4) is located among the others, which makes it a kind of central business district (CBD) of the city. All the districts are connected to each other via two-way roads passing through the 4th district (Figure 3.1).

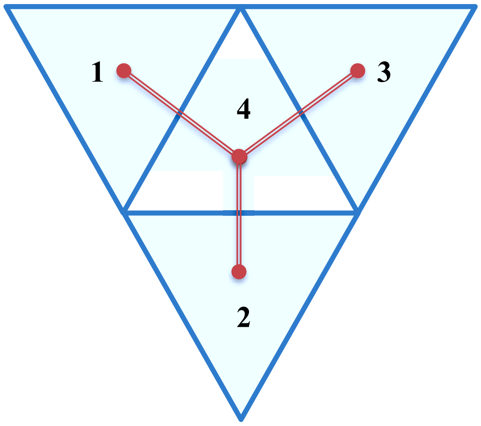


Figure 3.1 Locations of districts within the city

The proposed model, in this Section, is studied using the above synthetic city set-up and under the homogenous scenario of the increased capacity of a (private) transport between districts 1 and 3. Here, I introduce the elements of heterogeneity (attributes) of the households sequentially. First, households are differentiated only in accordance with their residential locations (i) and working locations (w). In the next step, preferred commuting mode (m) is added to these categories. Commuting mode options represented in this study are public transport and private transport. In the third step, another category for households (g) is introduced where households are categorised according to factor types they own. The first group of households owns the capital (business + housing) and the second group owns the labour. This makes the first group "capital owners" and second group "workers". It should be noted that there is only one type of labour (single wage level) in the economy.

In all these cases, I assume that the households maximise their utilities consuming housing units (floor space) and one type of consumption good. This leads to having a one-sector economy in this city. Housing stock is assumed to be fixed. Housing rents are shared equally among households for the first two scenarios, while these rents are collected by capital owners in the third scenario. All transport costs the households bear is added to GDP, travels are not considered in household utility function as a utility increasing component like housing and consumption goods, though. However, the effects of transport costs are two-fold. On one hand, it has a flat-rate shrinking effect on a household budget in accordance with the pair of housing location and working location. On the other hand, the disutility of travel, which is associated with spent time for a travel, is considered in location choice decisions of households.

As already mentioned above, in this scenario, households are categorised according to their residential locations (1, 2, 3, 4) and working locations (1, 2, 3, 4). Rents for capitals (business + housing) are shared among households equally. The matrix showing the number of households for each locational pair constitutes OD matrix of the city (Table 3.1). It is assumed that there are 20,000 households in total and most households are prone to do within-district journeys.

Table 3.1 Number of households travelling between districts

		TO			
		1	2	3	4
FROM	1	2,500	500	500	1,500
	2	500	2,500	500	1,500
	3	500	500	2,500	1,500
	4	500	500	500	3,500

Turning to journeys to be done by these households and related travel costs, travel time required for within-district journeys are assumed to be fixed and travel time required for other journeys are calculated using above OD matrix and certain transport parameters[11] associated with the travel model. Travel costs are assumed to be equal to travel times.

---

[11] A=8, B=0.15 and Q=1000

Table 3.2 Travel times for journeys between districts

		TO			
		1	2	3	4
FROM	1	2	24.62	24.62	15.86
	2	24.62	2	24.62	15.86
	3	24.62	24.62	2	15.86
	4	10.76	10.76	10.76	2

For calibration purposes, all households are assumed to consume an equal amount of consumption goods. The quantity of consumption good for each household is 50. Housing consumptions (rents paid to owners) in floor space are varying with respect to household categories and calculated in a way to satisfy the following set of equations:

$$\begin{aligned} & d(i,w)+c(i,w)+tc(i,w)=k+l+h \\ & h=\sum_i\sum_w n(i,w)\cdot d(i,w)\Big/\sum_i\sum_w n(i,w) \end{aligned} \tag{21}$$

where households use their budgets (*k*: capital rent, *l*: wage and *h*: housing rent) for their consumption needs (*c*: consumption good, *d*: housing and *tc*: transport cost) and *n(i,w)* denotes the number of households with residential location *i* and working location *w*. Housing consumptions of households are displayed in Table 3.3.

Table 3.3 Housing consumptions of households

		TO			
		1	2	3	4
FROM	1	42.62	20	20	28.76
	2	20	42.62	20	28.76
	3	20	20	42.62	28.76
	4	33.86	33.86	33.86	42.62

Households maximise their utility in accordance with the following utility function:

$$U_{iw}(d,c)=\left(\alpha_{iw}c_{iw}^{\rho}+\alpha_{iw}^{h}d_{iw}^{\rho}\right)^{1/\rho}-\gamma_{iw}\tau_{iw} \tag{22}$$

The household budget constraint can be written as follows:

$$-M_{iw} + r_i d_{iw} + pc_{iw} + \kappa_{iw} \leq 0 \tag{23}$$

where M is the total income of a household, r is the rental rate for housing, p is the price for consumption good and κ is travelling cost. As previously mentioned, earned incomes (wages) and unearned incomes (rents for capitals and dwellings) constitute the household budget. Therefore, household budget (M) can be written as in the following equation:

$$M_{iw} = l + \delta e_{iw}^{K} + \sum_{i'} r_{i'} e_{iw}^{H}\left(i'\right) \tag{24}$$

where e^K and e^H are the endowments of capital and dwelling of a household respectively. Using utility function and a budget constraint for households, demand functions for the consumption good and housing units in terms of prices can be written as follows:

$$c_{iw} = \left(\frac{\alpha_{iw}}{p}\right)^{\sigma} \frac{M_{iw} - \kappa_{iw}}{\left(\alpha_{iw}^{h}\right)^{\sigma} r_i^{1-\sigma} + \left(\alpha_{iw}\right)^{\sigma} p^{1-\sigma}} \tag{25}$$

$$d_{iw} = \left(\frac{\alpha_{iw}^{h}}{r_i}\right)^{\sigma} \frac{M_{iw} - \kappa_{iw}}{\left(\alpha_{iw}^{h}\right)^{\sigma} r_i^{1-\sigma} + \left(\alpha_{iw}\right)^{\sigma} p^{1-\sigma}} \tag{26}$$

Using MNL household location choice probabilities and exogenously given number of households travelling to a district $N\left(w\right)$, the number of households residing at a specific location is calculated by using the following equation.

$$N_i\left(w\right) = \frac{\exp\left[\left(\alpha_{iw} c_{iw}^{\rho} + \alpha_{iw}^{h} d_{iw}^{\rho}\right)^{1/\rho} - \gamma_{iw}\tau_{iw}\right]}{\sum_{j} \exp\left[\left(\alpha_{jw} c_{jw}^{\rho} + \alpha_{jw}^{h} d_{jw}^{\rho}\right)^{1/\rho} - \gamma_{jw}\tau_{jw}\right]} N\left(w\right) \tag{27}$$

Integrating the above setting with the travel model, a capacity increasing scenario is tested. In this scenario, a direct link between districts 1 and 3 is proposed. It is assumed that technical properties of the new link would be identical with technical properties (properties affecting travel time, i.e. capacity, length) of the existing ones. (Figure 3.2)

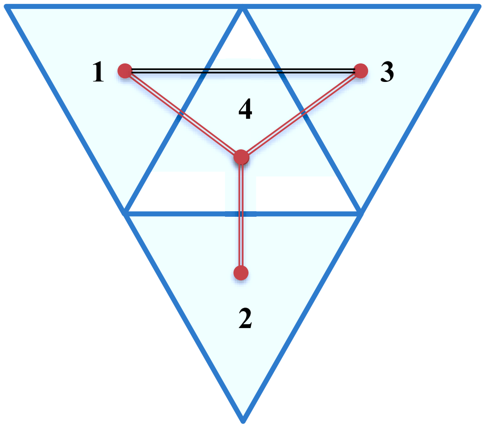


Figure 3.2 New link between district 1 and district 3

Results of the model indicate that interregional transport costs at equilibrium point would become different than initial transport costs after implementation of the new link. As shown in Table 3.4, at some routes, about 8 per cent deviation is observed. To give an example, at the equilibrium point, travel time from District 2 to District 4 would be 7.97 per cent lower than initial expectation while travel time from District 1 to District 4 would be 7.13 per cent higher.

Table 3.4 Impact of a new link on travel times

		Travel times (initial)				Travel times (equilibrium)			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	2	21.16	10.01	12.40	2	22.23	10.24	13.28
	2	24.01	2	24.01	15.86	22.69	2	22.69	14.60
	3	10.01	21.16	2	12.40	10.24	22.23	2	13.28
	4	10.15	10.76	10.15	2	10.09	10.95	10.09	2

This finding is important to understand the role of integrated models in the evaluation of transport policies and investments, and to have more accurate predictions. The main reason for having different travel time figures in two approaches is that people change their locations in response to changing the accessibility of districts. Without considering of this phenomenon, it is very unlikely to predict impacts of this kind of projects accurately. Table 3.5 shows how household distribution would change substantially. As expected, improvement in accessibility between District 1 and District 3 increases the number of households travelling between these two districts significantly while the number of households travelling within zones, which benefit from the lowest transport costs at the initial setting, decreases.

Table 3.5 Impact of a new link on the household spatial distribution

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	2500	500	500	1500	1991.81	550.69	1123.70	1612.78
	2	500	2500	500	1500	432.11	2414.62	432.11	1485.91
	3	500	500	2500	1500	1123.70	550.69	1991.81	1612.78
	4	500	500	500	3500	452.38	484.01	452.38	3288.52

This shift in people's preferences to reside in districts 1 and 3 should have an impact on dwelling prices. Results of the model indicate that relative prices of these districts would become higher than the ones of the others. As shown in Table 3.6, the highest erosion in housing prices would exist in District 4, which is the central district of the city. This distinction can be attributed to a relative decrease in accessibility of District 4 due to improvements in districts 1 and 3.

Table 3.6 Impact of a new link on housing prices

Initial				Equilibrium			
1	2	3	4	1	2	3	4
1.00	1.00	1.00	1.00	0.97	0.92	0.97	0.88

The model shows that price changes in housing would affect household decisions on consuming housing units in floor space. Table 3.7 indicates that households enjoy the relative price reduction in District 4, so the highest increase in demand is witnessed at this district and District 2 is the follower. For districts 1 and 3, where the accessibility is improved the most, slight changes in housing demand take place in general due to relatively high housing prices. However, for households travelling between these two districts, housing demand increases with a rate outpacing any other rate of increase. That decreasing transport cost gives way to use the extra budget for utility increasing consumptions can be deemed as the main reason behind this distinction. It should also be noted that households travelling within districts 1 and 3 are the only groups having reduced housing demand among all groups of people.

Considering consumption good demands of people, which is analysed below, I can say that decrease in total output due to a decrease in transport costs would cause some level of decrease in household income. For this reason, some groups of people, which are already enjoying low transport costs, would be affected in a negative way. This finding is important that not every group of people would be influenced in a positive way by implemented policies or investments. Although, as in this case, an investment improves accessibility in a city, there may be some groups of people already enjoying poor accessibility. This should lead one to elaborate on impacts of interventions to understand how their impacts differ in accordance with different groups and what kind of additional instruments one should consider removing negative consequences threatening individual rationality of different groups.

Table 3.7 Impact of new link on housing demand

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	42.62	20.00	20.00	28.76	42.34	20.35	23.84	29.36
	2	20.00	42.62	20.00	28.76	21.02	44.24	21.02	30.09
	3	20.00	20.00	42.62	28.76	23.84	20.35	42.34	29.36
	4	33.86	33.86	33.86	42.62	36.26	35.88	36.26	45.55

Turning to consumer preferences of households on consumption good, the model provides interesting results as in previous analysis on housing demand. As explained before, decrease in demand of households doing within-district journeys in districts 1 and 3 can be explained by a reduction in total output of the economy. This time, besides these groups of people, people doing within district journeys in District 2 and people travelling from District 4 to District 2 suffer from this fact although to a lesser extent. However, as in demand change in housing, household groups doing journeys between districts 1 and 3 enjoy the improvement in accessibility the most, as expected.

Table 3.8 Impact of a new link on consumption good demand

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	50.00	50.00	50.00	50.00	49.04	50.23	58.83	50.40
	2	50.00	50.00	50.00	50.00	50.33	49.71	50.33	50.10
	3	50.00	50.00	50.00	50.00	58.83	50.23	49.04	50.40
	4	50.00	50.00	50.00	50.00	50.26	49.74	50.26	50.16

3.2.3 Scenario I-2: Model with Location Categories and Travel Modes

In this step, households' preferences on their commuting modes are added to the model structure. Therefore, households are categorised according to their residential locations and working locations, and preferred commuting mode between these locations. As in the first case, rents for business capitals and dwelling units are shared among households equally. This time, 23,800 households (13,700 private transport users and 10,100 public transport users) are assumed to reside in the city. Numbers of households travelling between regions with respect to commuting modes are listed in Table 3.9 and Table 3.10.

Table 3.9 Number of travelling households (private transport)

		TO			
		1	2	3	4
FROM	1	1,000	600	500	1,000
	2	500	600	500	1,500
	3	600	700	1,000	1,000
	4	900	800	1,000	1,500

Table 3.10 Number of travelling households (public transport)

		TO			
		1	2	3	4
FROM	1	1,000	300	400	1,500
	2	600	1,000	700	1,000
	3	300	400	500	1,000
	4	400	300	200	500

This time, there is a more complex travel time and cost structure when compared to the first case. For private transport mode, travel times and travel costs are assumed to be equal as in the first scenario, though. Travel time required for private within-district journeys are assumed to be fixed with the value of 5. For this mode, travel time required for other journeys are calculated as in the first scenario. However, travel time for public transport journeys does not vary with congestion level but with route lengths. Travel time for within-district journeys is assumed 10 while it is 15 for adjacent districts and 30 for the others. Public transport cost for within-district journeys is assumed 4 and 10 for all the other journeys regardless of route lengths. Travel times and travel costs for each mode are provided in Tables 3.11 and 3.12.

Table 3.11 Travel times for private and public transport

		Private Transport				Public Transport			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	5	21.83	21.32	10.92	10	30	30	15
	2	24.26	5	24.26	13.86	30	10	30	15
	3	22.60	23.12	5	12.20	30	30	10	15
	4	10.40	10.92	10.40	5	15	15	15	10

Table 3.12 Travel costs for private and public transport

		Private Transport				Public Transport			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	5	21.83	21.32	10.92	4	10	10	10
	2	24.26	5	24.26	13.86	10	4	10	10
	3	22.60	23.12	5	12.20	10	10	4	10
	4	10.40	10.92	10.40	5	10	10	10	4

As in the first scenario, all households are assumed to consume an equal amount of consumption goods with the quantity of 50 units and housing consumptions in floor space are assumed to be varying with respect to household categories. Housing consumptions are calculated mathematically in a way to satisfy the following set of equations, which is a modified version of equation set (21) with an additional household category index *m* denoting commuting mode:

$$\begin{gathered} d\left(i,w,m\right)+c\left(i,w,m\right)+tc\left(i,w,m\right)=k+l+h \\ h=\sum_{i}\sum_{w}\sum_{m}n\left(i,w,m\right)\cdot d\left(i,w,m\right)\Big/\sum_{i}\sum_{w}\sum_{m}n\left(i,w,m\right) \end{gathered} \tag{28}$$

After solving above equation set, I would find households' housing consumptions in floor space as in the following table.

Table 3.13 Housing consumptions of households

		Private Transport				Public Transport			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	39.26	22.42	22.94	33.34	40.26	34.26	34.26	34.26
	2	20.00	39.26	20.00	30.40	34.26	40.26	34.26	34.26
	3	21.66	21.14	39.26	32.06	34.26	34.26	40.26	34.26
	4	33.86	33.34	33.86	39.26	34.26	34.26	34.26	40.26

Household utility function, household budget constraint and household budget equation are revised accordingly with household indices as in Equation (29), Equation (30) and Equation (31):

$$U_{iwm}\left(d,c\right)=\left(\alpha_{iwm}c_{iwm}^{\rho}+\alpha_{iwm}^{h}d_{iwm}^{\rho}\right)^{1/\rho}-\gamma_{iwm}\tau_{iwm} \tag{29}$$

$$-M_{iwm}+r_{i}d_{iwm}+pc_{iwm}+\kappa_{iwm}\leq 0 \tag{30}$$

$$M_{iwm}=l+\delta e_{iwm}^{K}+\sum_{i^{'}}r_{i^{'}}e_{iwm}^{H}\left(i^{'}\right) \tag{31}$$

Defining the above set of equations as a household utility maximisation problem would lead to following demand functions for the consumption good and housing units in terms of prices:

$$c_{iwm}=\left(\frac{\alpha_{iwm}}{p}\right)^{\sigma}\frac{M_{iwm}-\kappa_{iwm}}{\left(\alpha_{iwm}^{h}\right)^{\sigma}r_{i}^{1-\sigma}+\left(\alpha_{iwm}\right)^{\sigma}p^{1-\sigma}} \tag{32}$$

$$d_{iwm}=\left(\frac{\alpha_{iwm}^{h}}{r_{i}}\right)^{\sigma}\frac{M_{iwm}-\kappa_{iwm}}{\left(\alpha_{iwm}^{h}\right)^{\sigma}r_{i}^{1-\sigma}+\left(\alpha_{iwm}\right)^{\sigma}p^{1-\sigma}} \tag{33}$$

Using MNL household location and travel mode choice probabilities and exogenously given number of households travelling to a specific region, *N(w)*, the number of households residing at a specific location and using a specific travelling mode is calculated by using the following equation.

$$N_{i,m}\left(w\right)=\frac{\exp\left[\left(\alpha_{iwm}c_{iwm}^{\rho}+\alpha_{iwm}^{h}d_{iwm}^{\rho}\right)^{1/\rho}-\gamma_{iwm}\tau_{iwm}\right]}{\sum_{j}\sum_{m'}\exp\left[\left(\alpha_{jwm'}c_{jwm'}^{\rho}+\alpha_{jwm'}^{h}d_{jwm'}^{\rho}\right)^{1/\rho}-\gamma_{jwm'}\tau_{jwm'}\right]}N\left(w\right) \tag{34}$$

Equations for the production side of the economy are not affected by the new setting of household categories. Therefore, producers solve the same cost minimisation problem for a level of production output defined in the first scenario.

In this scenario, a direct link between districts 1 and 3 is proposed as illustrated previously in Figure (3.2). It should be noted that this link is used by only private cars although its technical properties are the same as the existing links' properties.

Results of the model indicate that interregional transport costs for private transport mode at equilibrium point would become different than initial transport costs after implementation of the new link. As illustrated in Table 3.14, travel time difference between initial expectation level and equilibrium level becomes more than 4 per cent for some routes. At equilibrium point, travel times from District 3 to District 4 and District 2 would be 4.14 per cent and 3.34 per cent higher than initial expectations respectively. There is a general travel time decrease for journeys from District 2 when I compare equilibrium levels with initial levels. To give an example, travel time from District 2 to District 4 would be 2.54 per cent lower.

Table 3.14 Impact of a new link on travel times (private transport)

		Travel times (initial)				Travel times (equilibrium)			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	5	19.90	8.01	8.98	5	20.33	8.05	9.18
	2	22.44	5	22.62	13.86	22.01	5	22.12	13.51
	3	8.02	20.17	5	9.25	8.08	20.78	5	9.64
	4	8.58	10.92	8.76	5	8.51	11.15	8.61	5

Tables 3.15 and 3.16 show initial and equilibrium levels of household spatial distribution in the city for each travel mode. As expected, building a direct link between districts 1 and 3 improves accessibility levels of these districts. For private

transport users, this improvement would lead to increase in the number of households travelling between these two districts significantly. To be clearer, the number of households travelling from District 1 to District 3 increases about 54 per cent and while this figure for journeys in reverse direction is about 44 per cent.

Another impact is on private transport. Building a new link serving only to private transport increases the attractiveness of private transport when compared to public transport. As the most obvious consequence of this, the number of private transport users increases from 13,700 to 14,084. This means that an obvious shift in transport alternatives would happen because of this capacity increase.

Table 3.15 Impact of a new link on household distribution (private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	1000	600	500	1000	933.67	621.40	774.09	1052.38
	2	500	600	500	1500	500.95	590.18	496.60	1468.87
	3	600	700	1000	1000	865.78	736.06	931.17	1079.85
	4	900	800	1000	1500	855.49	781.67	927.57	1468.72

As shown in Table 3.16, the number of public transport users for each location pair decreases at varying levels. It should be noted that these decreases for journeys to districts 1 and 3 are obviously higher than the others.

Table 3.16 Impact of a new link on household distribution (public transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	1000	300	400	1500	933.59	296.29	372.02	1475.48
	2	600	1000	700	1000	557.93	983.73	648.03	979.10
	3	300	400	500	1000	280.92	395.98	465.50	985.97
	4	400	300	200	500	371.68	294.70	185.01	489.63

It is obvious that shifts in people' preferences in residential location and travelling mode would have an impact on economic parameters. Results of the model indicate that relative prices in districts 1 and 3 would become substantially higher than the ones at the other regions as expected. The price increase for district 3 would be 8 per cent while price decrease for District 4, which is CBD, would be as high as 4 per cent. (Table 3.17)

Table 3.17 Impact of a new link on housing prices

Initial				Equilibrium			
1	2	3	4	1	2	3	4
1.00	1.00	1.00	1.00	1.04	0.97	1.08	0.96

Table 3.18 and Table 3.19 show how housing demand of households using private transport and public transport changes respectively. I notice a general demand increase for districts 2 and 4 where relative housing prices decrease. Considering together increases in price and number of resident households for districts 1 and 3 would easily explain slight decreases in housing demand for these regions. However, for private transport users, it should be noted that housing demand of households travelling between District 1 and District 3 increases significantly (Table 3.18). Increase in private transport accessibility for people travelling between these districts is the underlying reason for this. Since there is no improvement for public transport users travelling between districts 1 and 3, I cannot mention about a distinctive increase in housing demand for this group of people, but slight demand increases for people in districts 2 and 4 and slight decreases for the rest.

Table 3.18 Impact of a new link on housing demand (private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	39.26	22.42	22.94	33.34	38.22	22.37	26.47	33.17
	2	20.00	39.26	20.00	30.40	21.15	40.27	21.12	31.30
	3	21.66	21.14	39.26	32.06	24.86	20.87	37.26	31.45
	4	33.86	33.34	33.86	39.26	35.80	34.38	35.75	40.61

Table 3.19 Impact of a new link on housing demand (public transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	40.26	34.26	34.26	34.26	39.19	33.39	33.39	33.39
	2	34.26	40.26	34.26	34.26	35.13	41.29	35.13	35.13
	3	34.26	34.26	40.26	34.26	32.57	32.57	38.20	32.57
	4	34.26	34.26	34.26	40.26	35.43	35.43	35.43	41.65

The model shows that households' consuming preferences on consumption good would be affected as their preferences on housing. Since transport costs for households using public transport for their commuting journeys do not change due to the new link between districts 1 and 3, one can see the impact of housing price changes on consumption decisions of households. To make it clearer, consumption good demand of households residing in districts 1 and 3 slightly decreases while one of them residing in other districts increases without any exception (Table 3.21). It should be noted that these changes are moving along a narrow interval and the maximum change becomes only 1.38 per cent. On the other hand, for private transport users, only two groups of households (among 16 groups) demand less consumption goods when compared to the setting before building the new link (Table 3.20). For these people, consumption good demand decreases by 0.48 per cent and 1.26 per cent. In addition to this, humble rates, as in public transport, give way to quite high ones. To give an example, after implementing the new link, households travelling between districts 1 and 3 using their own private cars demand more consumption goods more by the rates of 17.96 per cent and 19.40 per cent. This, obviously, can be linked to general improvement in transport costs for private transport, particularly for the journeys between districts 1 and 3.

Table 3.20 Impact of a new link on consumption good demand (private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	50.00	50.00	50.00	50.00	49.76	50.99	58.98	50.85
	2	50.00	50.00	50.00	50.00	52.13	50.56	52.05	50.76
	3	50.00	50.00	50.00	50.00	59.70	51.33	49.37	51.02
	4	50.00	50.00	50.00	50.00	51.81	50.53	51.74	50.69

Table 3.21 Impact of a new link on consumption good demand (public transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	50.00	50.00	50.00	50.00	49.75	49.81	49.81	49.81
	2	50.00	50.00	50.00	50.00	50.55	50.56	50.55	50.55
	3	50.00	50.00	50.00	50.00	49.45	49.45	49.35	49.45
	4	50.00	50.00	50.00	50.00	50.67	50.67	50.67	50.69

Apart from the previous scenario, introducing a new group of people (public transport users) has enabled me to understand the impact of the new link on different groups and what type of equity problems to be faced. Without making any improvement in public transport, even not making public transport available on the new link, public transport users would become losers of the proposed “improvement”.

3.2.4 Scenario I-3: Model with Location Categories, Travel Modes and Economic Groups

Next, I introduce a new attribute of heterogeneity to categorise households with respect to their endowments. As briefly discussed before, the first group of households (capital owners) owns the capital (business + housing) in the economy. Generated income for rented capitals is shared among this group equally. The second group of households (workers) owns the labour. There is only one type of labour that is employed in production activities. This leads to a single wage level in the economy.

Now, households are categorised according to their residential locations and working locations, preferred commuting mode between these locations and abovementioned economic groups they are in. As in the second scenario, 23,800 households (13,090 private transport users + 10,710 public transport users) are residing in the city. About 16 per cent of households (3,859 households) is assumed to be capital owners. It should be noted here that capital owners are assumed to be more apt to use their private vehicles for their commuting trips when compared to workers. About 84 per cent of capital owners uses private transport, while this figure is roughly half for workers. Numbers of households with different economic groups travelling between districts with respect to commuting modes are listed in Tables 3.22 and 3.23.

Table 3.22 Number of travelling households w.r.t. economic groups (private transport)

		Capital owners				Workers			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	324	141	139	328	880	212	270	935
	2	110	162	180	365	397	536	492	1,230
	3	87	129	203	221	404	355	255	805
	4	203	171	185	283	801	906	750	631

Table 3.23 Number of travelling households w.r.t. economic groups (public transport)

		Capital owners				Workers			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	76	30	32	72	720	517	459	1,165
	2	22	30	36	85	571	872	492	820
	3	21	14	22	39	388	602	1,020	935
	4	44	5	43	57	252	18	222	1,029

For this scenario, for private transport mode, travel times and travel costs are assumed to be equal as in other scenarios. Travel time required for private within-district journeys is fixed to 5 and travel time required for other journeys is calculated using the travel model. As in the second scenario, travel time required for public transport journeys do not change due to the congestion level but with route lengths. Travel time and cost structures for this mode are adopted from the previous scenario without any change.

It should also be noted that transport time and cost figures do not change with the economic group of households. The categories effective in these figures are households' locations (both residential and working) and their preferences on commuting mode.

Since there are distinctive income levels for each economic group of households, I would introduce different consumption levels for these groups. Capital owners consume more consumption goods than workers do. Consumption level for capital owners is assumed to be 400 and it is assumed to be 40 for workers. As in previous scenarios, housing consumptions in floor space are assumed to be varying with respect to household categories. Housing consumption for each household category is calculated using the following set of equations with an additional household category index *g* (1=capital owners, 2=workers) denoting the economic group of households:

$$\begin{aligned}
&d\left(i,w,m,g=1\right)+c\left(i,w,m,g=1\right)+tc\left(i,w,m\right)=k+h\\
&d\left(i,w,m,g=2\right)+c\left(i,w,m,g=2\right)+tc\left(i,w,m\right)=l\\
&h=\sum_i\sum_w\sum_m\sum_g n\left(i,w,m,g\right)\cdot d\left(i,w,m,g\right)\Big/\sum_i\sum_w\sum_m n\left(i,w,m,g=1\right)
\end{aligned} \tag{35}$$

Solving this equation set mathematically would lead to households' housing consumptions in floor space as in the following tables. Please notice that capital owners' housing consumptions are higher than workers' consumptions, nevertheless, the difference is not as much as in consumption goods.

Table 3.24 Housing consumptions of households (private transport)

		Capital owners				Workers			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	72.36	56.82	56.36	66.84	32.99	17.45	16.99	27.46
	2	50.07	72.36	50.00	60.48	10.69	32.99	10.63	21.10
	3	56.55	56.94	72.36	66.96	17.17	17.57	32.99	27.58
	4	66.95	67.35	66.88	72.36	27.58	27.97	27.51	32.99

Table 3.25 Housing consumptions of households (public transport)

		Capital owners				Workers			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	73.36	67.36	67.36	67.36	33.99	27.99	27.99	27.99
	2	67.36	73.36	67.36	67.36	27.99	33.99	27.99	27.99
	3	67.36	67.36	73.36	67.36	27.99	27.99	33.99	27.99
	4	67.36	67.36	67.36	73.36	27.99	27.99	27.99	33.99

Household utility function, household budget constraint and household budget equation are revised accordingly with household indices as follows:

$$U_{iwmg}\left(d,c\right)=\left(\alpha_{iwmg}c_{iwmg}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right)^{1/\rho}-\gamma_{iwmg}\tau_{iwm} \tag{36}$$

$$-M_{iwmg} + r_i d_{iwmg} + pc_{iwmg} + \kappa_{iwm} \leq 0 \tag{37}$$

$$M_{iwmg} = \delta e^{K}_{iwmg} + \sum_{i'} r_{i'} e^{H}_{iwmg}\left(i'\right) \;\; \left(g = 1\right) \tag{38}$$

$$M_{iwmg} = l \;\; \left(g = 2\right) \tag{39}$$

Solving household utility maximisation problem using the above setting would lead to the following demand functions for consumption good and housing units in terms of prices:

$$c_{iwmg} = \left(\frac{\alpha_{iwmg}}{p}\right)^{\sigma} \frac{M_{iwmg} - \kappa_{iwm}}{\left(\alpha^{h}_{iwmg}\right)^{\sigma} r_i^{1-\sigma} + \left(\alpha_{iwmg}\right)^{\sigma} p^{1-\sigma}} \tag{40}$$

$$d_{iwmg} = \left(\frac{\alpha^{h}_{iwmg}}{r_i}\right)^{\sigma} \frac{M_{iwmg} - \kappa_{iwm}}{\left(\alpha^{h}_{iwmg}\right)^{\sigma} r_i^{1-\sigma} + \left(\alpha_{iwmg}\right)^{\sigma} p^{1-\sigma}} \tag{41}$$

For any group of households, number of ones residing at a specific location and using a specific travelling mode is:

$$N_{i,m}\left(w,g\right) = \frac{\exp\left[\left(\alpha_{iwmg} c^{\rho}_{iwmg} + \alpha^{h}_{iwmg} d^{\rho}_{iwmg}\right)^{1/\rho} - \gamma_{iwmg}\tau_{iwm}\right]}{\sum_{j}\sum_{m'} \exp\left[\left(\alpha_{jwm'g} c^{\rho}_{jwm'g} + \alpha^{h}_{jwm'g} d^{\rho}_{jwm'g}\right)^{1/\rho} - \gamma_{jwm'g}\tau_{jwm'}\right]} N\left(w,g\right) \tag{42}$$

In this scenario, as in the first two scenarios, a direct link between districts 1 and 3 is proposed as illustrated previously in Figure 3.2. This link is used by only private cars and it is technically identical with the existing links.

When I compare the results of interregional transport times of private transport for initial setting just after implementing the new link and equilibrium level, I find that some results differ at high rates. To give an example, at the equilibrium level, travel time from District 2 to District 4 would be 15.45, while it is initially expected to be 16.88 (Table 3.26). As already explained previously, this explains why people's movements around the city should be considered to have accurate predictions and implement proper policies and projects.

Table 3.26 Impact on private transport mode travel times

		Travel times (initial)				Travel times (equilibrium)			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	5	19.04	8.00	9.02	5	19.32	8.07	9.14
	2	25.66	5	25.88	16.88	24.04	5	24.18	15.45
	3	8.01	18.79	5	8.78	8.10	19.18	5	9
	4	8.78	10.01	9	5	8.59	10.18	8.73	5

Table 3.27, Table 3.28, Table 3.29 and Table 3.30 provide household spatial distribution for each group. As for people's movements in the city and their travel mode preferences, it can be concluded that building a direct link carrying private transport traffic between districts 1 and 3 increases private transport demand. The number of households using private transport increases from 13,090 to 13,619 at a rate of about 4 per cent. When I look at the details of this increase, as expected, increases in the number of households (both capital owners and workers) travelling between districts 1 and 3 are the main factors. For capital owners, the number of households travelling from District 1 to District 3 increases by 46.14 per cent, while the number of households travelling in opposite direction increases by 143.28 per cent (Table 3.27). For workers, the number of households travelling from District 1 to District 3 increases by 126.06 per cent, while the number of households travelling in opposite direction increases by 67.95 per cent (Table 3.28).

Table 3.27 Impact on household spatial distribution (capital owners+private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	324	141	139	328	260.87	143.97	203.14	326.25
	2	110	162	180	365	107.64	157.87	172.12	359.06
	3	87	129	203	221	211.65	137.93	183.17	237.75
	4	203	171	185	283	176.23	164.44	164.90	276.18

Table 3.28 Impact on household spatial distribution (workers + private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	880	212	270	935	805.40	230.35	610.35	953.41
	2	397	536	492	1,230	418.94	528.47	494.69	1212.90
	3	404	355	255	805	678.53	381.41	225.78	843.47
	4	801	906	750	631	743.59	890.39	694.85	623.29

These changes due to improvement in private transport accessibility of districts 1 and 3 would lead to substantial changes in the number of residents for each district. District 3 is the leading region attracting new households with an increase of 5.15 per cent. As expected, the number of households in District 1 increases by 2.46 per cent while those in districts 2 and 4 decrease by 2.54 per cent and 4.92 per cent respectively.

Table 3.29 Impact on household spatial distribution (capital owners + public transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	76	30	32	72	61.18	29.58	28.31	71.73
	2	22	30	36	85	17.48	29.24	31.41	83.53
	3	21	14	22	39	17.35	14.16	19.83	39.84
	4	44	5	43	57	34.59	4.81	37.12	55.66

Table 3.30 Impact on household spatial distribution (workers + public transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	720	517	459	1,165	658.95	511.04	404.66	1,155.89
	2	571	872	492	820	520.91	859.85	432.28	810.84
	3	388	602	1,020	935	357.40	598.81	902.86	933.53
	4	252	18	222	1,029	229.29	17.69	194.54	1,016.66

Turning to economic impacts of shifts in people' preferences in residential location and travelling mode, results of the model show that relative prices in districts 1 and 3, particularly District 3, would become substantially higher than the ones at the other locations as expected. District 3 is the region where prices increase the most with a rate of about 9 per cent while price increase in District 1 is only 1 per cent. This result is matching with increases in housing demand for these regions as explained above. It should be noted that, in this scenario, price differences among districts becomes more obvious when compared to the previous one. Besides significant price increase in District 3, housing price for District 4 (CBD) decreases by 7 per cent. Please notice that this figure was about 4 per cent in the previous scenario (Table 3.31).

Table 3.31 Impact of a new link on housing prices

Initial				Equilibrium			
1	2	3	4	1	2	3	4
1.00	1.00	1.00	1.00	1.01	0.96	1.09	0.93

Table 3.32, Table 3.33, Table 3.34 and Table 3.35 provide housing demand information for each type of household. Model results indicate that, in line with changes in the number of households and housing prices, a general consumption (in floor space) increase is observed for districts 2 and 4, and, other regions have a reverse situation. However, when I look at the whole picture closer, for private transport users, housing consumption of this group increases in some cases. Because of decreasing private transport cost (particularly between districts 1 and 3) some households increase their housing consumption. To give an example, workers travelling from District 1 to District 3 would increase their housing consumption by 22.12 per cent, which is the highest increase rate in housing consumption. This rate is followed by the housing consumption increase rate of workers travelling in the reverse direction with the value of 15.54 per cent. This shows how improvements in accessibility and transport costs would affect final consumption, albeit an increase in housing prices. Another important result that should be mentioned here is that improvements in accessibility and transport costs do not affect housing consumptions of capital owners as much as workers' consumptions. This can be linked to that these households would rather consume consumption goods more when compared to housing.

Table 3.32 Impact on housing demand (capital owners + private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	72.36	56.82	56.36	66.84	71.90	56.62	57.60	66.61
	2	50.07	72.36	50.00	60.48	51.38	73.78	51.30	61.83
	3	56.55	56.94	72.36	66.96	55.24	54.26	68.69	63.77
	4	66.95	67.35	66.88	72.36	69.95	70.07	69.87	75.34

Table 3.33 Impact on housing demand (workers + private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	32.99	17.45	16.99	27.46	32.81	17.74	20.74	27.89
	2	10.69	32.99	10.63	21.10	11.64	33.90	11.55	22.15
	3	17.17	17.57	32.99	27.58	19.84	16.96	30.97	26.49
	4	27.58	27.97	27.51	32.99	29.83	29.39	29.72	34.80

Table 3.34 Impact on housing demand (capital owners + public transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	73.36	67.36	67.36	67.36	72.90	66.94	66.94	66.94
	2	67.36	73.36	67.36	67.36	68.67	74.81	68.67	68.67
	3	67.36	67.36	73.36	67.36	63.96	63.96	69.63	63.96
	4	67.36	67.36	67.36	73.36	70.11	70.11	70.11	76.38

Table 3.35 Impact on housing demand (workers + public transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	33.99	27.99	27.99	27.99	33.81	27.84	27.84	27.84
	2	27.99	33.99	27.99	27.99	28.74	34.93	28.74	28.74
	3	27.99	27.99	33.99	27.99	26.32	26.32	31.90	26.32
	4	27.99	27.99	27.99	33.99	29.48	29.48	29.48	35.86

The model shows that households' preferences on consumption good would also be affected. As building a new link carrying only private transport traffic leads to improvement in private transport costs, major improvements in household consumptions are achieved for private transport users. To give an example, workers travelling from District 1 to District 3 using their own private vehicles would consume about 22.56 per cent more after the new link. This figure is about 20.64 per cent for this group of households travelling in the reverse direction. It should also be noted that a few numbers of groups using private transport would consume less consumption goods. This means that, for this group of people, achieved improvements in transport costs suppress well the increases in housing costs. (Table 3.36 and Table 3.37)

Table 3.36 Impact on consumption good demand (capital owners + private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	400	400	400	400	398.92	399.99	410.26	400.11
	2	400	400	400	400	402.82	400.28	402.75	401.33
	3	400	400	400	400	408.02	398.00	396.46	397.81
	4	400	400	400	400	402.78	401.08	402.72	401.36

Table 3.37 Impact on consumption good demand (workers + private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	40	40	40	40	39.94	40.80	49.02	40.76
	2	40	40	40	40	42.73	40.34	42.68	41.20
	3	40	40	40	40	48.26	40.32	39.22	40.11
	4	40	40	40	40	41.70	40.51	41.65	40.67

Turning to public transport users, model results indicate that, in line with changes in housing prices, a general consumption increase is observed for districts 2 and 4, and decrease for the others. Without any improvement in transport costs, changing housing costs would lead to these changes in households' consumption preferences. However, the most striking result is that workers doing the within-district journey in District 3 using public transport would consume 1.99 per cent less after the new link. This figure is the lowest among all types of households.

Table 3.38 Impact on consumption good demand (capital owners + public transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	400	400	400	400	398.91	398.92	398.92	398.92
	2	400	400	400	400	400.20	400.29	400.20	400.20
	3	400	400	400	400	396.60	396.60	396.43	396.60
	4	400	400	400	400	401.22	401.22	401.22	401.39

Table 3.39 Impact on consumption good demand (workers + public transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	40	40	40	40	39.93	39.94	39.94	39.94
	2	40	40	40	40	40.31	40.35	40.31	40.31
	3	40	40	40	40	39.29	39.29	39.21	39.29
	4	40	40	40	40	40.61	40.61	40.61	40.68

3.3 Scenario Analyses under Full Heterogeneity

In this Section, I provide the analyses of two different scenarios using the setting defined in Section 3.2.4, under full heterogeneity of households. The first scenario in this Section is introducing a new link between districts 1 and 3 as in Section 2. But, this time, this new link is used by only public transport vehicles. As the result of this link, public transport travel time between these districts is assumed to decrease from 30 to 20 units, while there is no change in public transport fee (Figure 3.3).

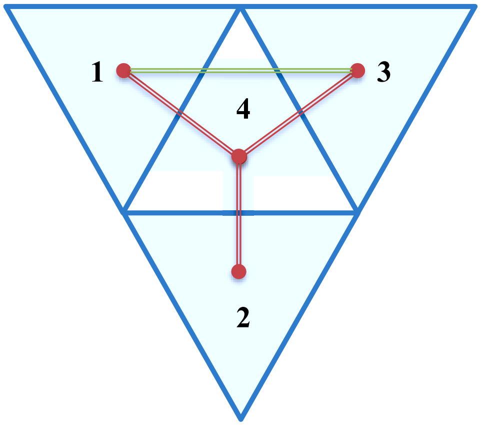


Figure 3.3 New public transport link between District 1 and District 3

The next scenario is introducing a fee for private transport users travelling to the District 4 (central district). This policy is often named as "cordon pricing" in the literature. Cordon pricing can be considered as a form of congestion charge (or congestion pricing) scheme, which comes to the fore to solve congestion problem although it was originally presented as a financing instrument for transport systems improvements.

The main rationale beneath congestion charge is that traffic congestion is a kind of market failure caused by "excessive demand" for a public good and implementing a "corrective charge" is needed to internalise traffic congestion externalities (Santos and Newbery, 2001). Although "French engineers" Jules Dupuit (1844) and Joseph Minard (1850) have provided visionary studies in this field, transport-related congestion and its pricing mechanisms have not been examined thoroughly before Arthur C. Pigou (1920) where he prepares the ground for taxation according to "marginal social cost" in road transport. In very early versions of Pigou's "The Economics of Welfare", it is claimed that rightly chosen measures can be used to increase the efficiency of transport. Pigou provides an illustration with two alternative routes and states that shifting some carts from one route to another would be possible by imposing differential taxation against a route. He claims, in this way, that significant level of relief can be provided in the taxed route with a slight trouble in the other route. This illustration is the milestone debate on congestion charging since Pigou proposes pricing not for financing infrastructure but for increasing the efficiency of "publicly owned roads" and the social welfare. Besides, Pigou criticizes the road transport taxation mechanism in a way that motorists do not pay for the damage they cause to the infrastructure.[12] However, in this scenario, I would not introduce a marginal social cost pricing scheme, but a fixed toll charged to drivers travelling to the central district.

3.3.1 Scenario II: Capacity and service improvement in public transport

In this scenario, rather than building a link carrying private transport traffic, a new public transport route is introduced between districts 1 and 3. As mentioned

---

[12] That alternative routes have different physical features is not explicitly stated in the book, but it is required to provide such traffic changes in different routes.

before, public transport fees do not change. A new public transport route leads to improvement in public transport service delivery and reduces travel time between these districts. (Tables 3.40 and 3.41)

The model results show that the public transport improvement in question would lead to certain changes in private transport journeys. Namely, travel times (and travel costs) for private transport journeys would decrease on most of the routes. This improvement should be attributed to the shift in travel mode, which is discussed in detail later in this part. It should be noted that, on certain routes, improvements in private transport travel times would be more than 2 per cent while there are slight increases in travel times on some routes.

Table 3.40 Travel times for journeys between districts for private and public transport

		Private Transport				Public Transport			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	5	20.54	21	10.52	10	30	**20**	15
	2	27.29	5	27.36	16.88	30	10	30	15
	3	20.81	20.42	5	10.40	**20**	30	10	15
	4	10.41	10.01	10.48	5	15	15	15	10

Table 3.41 Travel costs for journeys between districts for private and public transport

		Private Transport				Public Transport			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	5	20.54	21	10.52	4	10	10	10
	2	27.29	5	27.36	16.88	10	4	10	10
	3	20.81	20.42	5	10.40	10	10	4	10
	4	10.41	10.01	10.48	5	10	10	10	4

As mentioned above, the improvement in public transport would lead to a change in people’s travel mode preferences favouring public transport. After the improvement, the number of private transport users decrease from 13,090 to 12,926 at a rate of about 1.25 per cent, which is lower than the one of the previous scenario where a new link carrying private transport traffic is built between the same regions. In order to understand how this is reflected in different groups of people, I may have a look at people's movements in the city. Below tables show generated distribution of different groups of people with respect to their commuting locations, travel mode preferences and economic groups they belong to.

Tables 3.42 and 3.43 indicate that, regardless of their economic group, drivers travelling to District 1 and District 3 drop their private vehicles the most when compared to others travelling to other districts. However, when I look at these figures closer, I will see that number of drivers travelling from districts 1 and 3 to districts 2 and 4 increases. The main reason beneath this striking outcome should not be linked to travel times as the intervention in public transport leads to very little or no improvement in driving times on these routes, but to population increase in these districts. The number of public transport users, for both economic groups, travelling from districts 1 and 3 to districts 2 and 4 increases as well. As expected, the number of public transport users travelling between districts 1 and 3 would increase at a substantial rate. To give an example, the number of public transport users belonging to the capital owners group and travelling from District 3 to District 1 would increase by about 148 per cent.

Table 3.42 Impact on household distribution (capital owners + private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	324	141	139	328	310.85	142.01	136.17	329.80
	2	110	162	180	365	108.06	161.15	174.56	363.16
	3	87	129	203	221	85.80	130.47	196.28	222.87
	4	203	171	185	283	194.68	169.38	177.15	281.19

Table 3.43 Impact on household distribution (workers + private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	880	212	270	935	853.16	212.86	265.32	936.42
	2	397	536	492	1,230	391.46	535.29	480.77	1,227.14
	3	404	355	255	805	397.82	356.91	244.83	806.67
	4	801	906	750	631	776.16	903.76	723.82	630.05

Turning to the economic impacts of this intervention in public transport, results of the model show that relative housing prices in districts 1 and 3 would increase while prices in other regions would fall slightly. This result is in line with demand increase in housing in districts 1 and 3 owing to the public transport accessibility improvement. (Table 3.44) Recalling housing price changes in the previous scenario, changes for this scenario appear to be modest. However, it should be noted that magnitude of intervention plays a critical role in the magnitude of results. In this scenario, public transport travel time is assumed to decrease from 30 to 20. It must be born in mind that setting a different level of improvement would have caused different equilibrium levels, obviously. In line with changing housing prices and locations of households, housing demand for each household residing in districts 1 and 3 decreases and the one for other regions increases without any exceptions.

Table 3.44 Impact of new public transport route on housing prices

Initial				Equilibrium			
1	2	3	4	1	2	3	4
1.00	1.00	1.00	1.00	1.02	0.99	1.03	0.98

The model shows that changes in housing prices would affect households' consuming preferences on consumption good. As relative housing prices in districts 1 and 3 increase, household demand on consumption goods would decrease to compensate for this increase. Accompanying with the results on housing demand, this gives an important insight into people's mobility behaviours. The model results indicate that, after the improvement in public transport between districts 1 and 3, a higher number of households would begin to live in these districts although they would consume less on both dwellings and consumption goods. The main factor beneath this motivation is the improvement in travel time, which is not represented in household utility function in monetary terms. However, any changes in travel time conditions, accompanied with or without changes in transport costs, would affect utility function that is used in location choices of households. This should lead one to use a benchmarking indicator taking into consideration travel time valuations of households besides their consumptions on housing and other goods in order to compare different policies.

3.3.2 Scenario III: Introducing Cordon Pricing

In this scenario, rather than a capacity improving intervention, a toll for the entrances to the central district is introduced. Please note that trips starting at the central district is exempted from this duty and public transport fees remain unchanged. After this intervention, drivers travelling to District 4 would have to pay 10 units toll besides their transport costs. (Tables 3.45 and 3.46)

Table 3.45 Initial travel times for journeys for private and public transport

		Private Transport				Public Transport			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	5	20.54	21	10.52	10	30	30	15
	2	27.29	5	27.36	16.88	30	10	30	15
	3	20.81	20.42	5	10.40	30	30	10	15
	4	10.41	10.01	10.48	5	15	15	15	10

Table 3.46 Initial travel costs for journeys for private and public transport

		Private Transport				Public Transport			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	5	20.54	21	**20.52**	4	10	10	10
	2	27.29	5	27.36	**26.88**	10	4	10	10
	3	20.81	20.42	5	**20.40**	10	10	4	10
	4	10.41	10.01	10.48	5	10	10	10	4

Results show that, for this setting, introducing a cordon pricing results in unexpected (and backfiring) outcomes. Congestion charge schemes are often used to restrict private vehicle usage, promote public transport and, eventually, relieve traffic congestion. However, in this case, travel times to central district are increased after introduction of cordon pricing (See figures in bold in Table 3.47). This increase can be explained by increase in private car usage towards central district.

Table 3.47 Impact of cordon pricing on private transport travel times

		Travel times (initial)				Travel times (equilibrium)			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	5	20.54	21	**10.52**	5	20.56	20.98	**10.55**
	2	27.29	5	27.36	**16.88**	27.30	5	27.35	**16.92**
	3	20.81	20.42	5	**10.40**	20.79	20.43	5	**10.42**
	4	10.41	10.01	10.48	5	10.37	10.01	10.43	5

The number of households travelling to the central district increases, particularly for workers, although there is no substantial change in number of other households. To give an example, number of workers using private transport and travelling from District 2 to District 4 increases from 1,230 to about 1,263. This increase is even greater than total increase in private transport users, which is about 27.

Table 3.48 Impact on household spatial distribution (capital owners+private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	324	141	139	328	323.48	140.41	138.71	328.86
	2	110	162	180	365	108.47	161.57	177.98	365.81
	3	87	129	203	221	86.85	128.58	203.06	221.53
	4	203	171	185	283	205.10	172.52	186.96	282.87

Table 3.49 Impact on household spatial distribution (workers + private transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	880	212	270	935	882.87	210.42	269.67	942.10
	2	397	536	492	1,230	384.91	536.30	477.39	1,262.77
	3	404	355	255	805	403.19	352.97	256.05	811.05
	4	801	906	750	631	805.32	908.41	755.53	625.75

Tables 3.50 and 3.51 show how number of public transport users evolves after implementation of cordon pricing scheme around central district. As already mentioned, an unexpected shift in travel mode favouring private transport takes place.

Public transport loses about its 27 riders. It should be noted almost all these losses are coming from the group of workers and ones travelling to the central district play a critical role in this.

Table 3.50 Impact on household spatial distribution (capital owners + public transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	76	30	32	72	75.89	29.96	31.98	71.33
	2	22	30	36	85	21.90	29.93	35.89	84
	3	21	14	22	39	20.96	13.99	22.01	38.65
	4	44	5	43	57	44.35	5.04	43.41	56.96

Table 3.51 Impact on household spatial distribution (workers + public transport)

		Initial				Equilibrium			
		TO				TO			
		1	2	3	4	1	2	3	4
FROM	1	720	517	459	1,165	722.43	517.09	460.48	1,152.34
	2	571	872	492	820	572.06	872.61	493.30	810.61
	3	388	602	1,020	935	388.99	602.16	1,024.31	924.93
	4	252	18	222	1,029	253.25	18.05	223.27	1,020.45

Looking all the household distribution tables above together, number of households living and working in the central district decreases from 2,000 to 1,986. Given working locations of households remain unchanged, after introduction of cordon pricing, these households would move to the other regions. Relative increase in housing prices in District 4 can explain this movement. Table 3.52 shows that housing prices in District 4 would be higher than the others. This is an expected consequence of cordon pricing as travelling to this region from other regions would be more expensive. It is obvious that this relative price increase in transport would increase demand in centrally located houses. This finding can be supported by other studies in literature. Sato and Hino (2006) show that housing prices increase in and near the charge area using a spatial CGE model for road pricing in Tokyo. In an ex-post evaluation study, Tang (2016) shows that, using households' land registry transactions and census data, Western Extension Zone (WEZ) of congestion charge scheme in London increases in-cordon housing prices at a rate of 3.68 per cent when compared to houses within 1 km away from the boundary.

Table 3.52 Impact of cordon pricing on housing prices

Initial				Equilibrium			
1	2	3	4	1	2	3	4
1.00	1.00	1.00	1.00	0.96	0.96	0.97	1.00

Housing prices explain only a portion of households' movements. To explain remaining movements, particularly unexpected (and undesired) increase in private transport trips to the central district, one should look at households' behaviours closer. This requires investigating parameters explaining household preferences and heterogeneity among these households. Recalling household utility function in Equation (36),

$$U_{iwmg}\left(d,c\right)=\left(\alpha_{iwmg}c_{iwmg}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right)^{1/\rho}-\gamma_{iwmg}\tau_{iwm}$$

travel time valuation differs in accordance with the household group. Initial household distribution, so the initial setting, is critical to determine the levels of travel disutility parameter γ. At this point, I would go into details of movements of workers preferring to use private transport for their journeys from District 2 to District 4. Model results show that the number of this group of households increase unexpectedly although the cost of private transport increases due to cordon pricing and public transport offers shorter travel times for their journeys. This "subtler" consequence can be explained by the difference between disutility parameters γ for two travel modes. Travel disutility parameter for private transport is about 0.0032 while this figure is about 0.0234 for public transport making public transport on this route much more inferior to private transport option. This leads households travelling on this route to shift from public transport to private transport. Although the gap between parameter values for transport modes in favour of private transport is because of the initial setting (i.e. unelaborate distribution of households among districts, please note that for workers travelling on this route number of private transport users is set to be greater than the one of public transport users – See Tables 3.49 and 3.51), there may be structural problems, other than public transport accessibility in terms of travel costs and times, leading commuters not to prefer public transport as a commuting mode. This analysis (albeit using dataset based on a hypothetical basis) shows that transport policies may lead to unexpected outcomes without scrutinising the main problem.

Turning to other macroeconomic impacts of cordon pricing, housing demand of households travelling to the central district using their own private vehicles decrease as they would have increased transport cost after cordon pricing. Almost all the other household groups consume more on housing due to reductions in relative housing prices. There are slight decreases for some groups of households residing in the central district due to relatively high housing costs for this region.

It is interesting that economic group of households plays a distinct role in households' consumption good demands. Apart from households suffering from cordon pricing, households belonging to capital owners group would consume less on consumption goods while the other group of households consume more. This can be attributed to decreasing housing prices as housing rents constitute capital owners' income budget besides rents obtained for business capitals. For private transport users travelling to the central district, due to increased transport costs, the consumption good demand decreases substantially.

3.4 Discussion

I tested the proposed integrated model using a pseudo data set of a representative urban unit with four districts in this Chapter. Households are differentiated according to their residential location, working location, preferred commuting mode and social status. In the scenario analysis, I evaluate a set of alternative transport policies (i.e. capacity increase in private transport, public transport improvement, cordon pricing) and analyse the impacts of such policies on a set of parameters including household locational distribution, households' demand on consumption goods and housing, and housing prices observed.

I studied the model under three distinct scenarios, namely the capacity increase of private transport, the capacity increase in public transport and cordon pricing. In order to capture the relevance of representing the heterogeneity of households, I introduced elements of heterogeneity (location categories, travel mode, socio/economic groups) in sequence and discussed the results under the first scenario (a new private transport link between two districts of a city). The two other simulations are studied under the full heterogeneity set, namely introduction of increased capacity for public transport system and introduction of cordon pricing policy. All scenarios are carried out utilizing a synthetic data for a city with four residential/working districts.

Results show that heterogeneity among people in terms of their preferences and valuations is very critical in transport and land use policies. Without considering demographic structures of cities and producing accurate parameters for their preferences, toward policies would only lead to partial analyses.

CHAPTER 4

EVALUATING EFFECTS OF CROSSRAIL 2 PROJECT

4.1 Introduction

This Chapter introduces the urban CGE model constructed to analyse wider impacts of transport policies to be applied in Greater London Area (GLA) (Figure 4.1). First, I present the main features of the model. Next, the problems of households and firms are discussed in detail.

The model is in the urban-CGE tradition; based on the applied general equilibrium modelling and extended in the spatial dimension. Spaces are the boroughs in the GLA boundaries. I further extend the CGE model by adding sets of equations calculating shares of location and mode choices, and travel time and cost of private car journeys between residential and working locations. All the equations are solved simultaneously in the model.

The primary agents of the model are the individual households. They are differentiated in many respects including household income, household preferences on residential locations and transportation mode for commuting purpose. Households in the model are categorised with respect to their residential and working locations, commuting modes and income groups[13]. Households may change their residential location and/or commute mode preferences as a response to any change in urban conditions; working locations and income group of households are assumed to remain unchanged. Households are assumed to be owners of the total physical capital and housing stock in the economy, so they generate factor income by lending capital and labour factors to the firms and rent income by lending houses to other households.

---

[13] The detailed decomposition of the data w.r.t. the categorisation of the households is explained in Section 4.2.1.

Figure 4.1 Greater London Local Authorities (Boroughs)

On the production side, firms carry out production activities and distribute factor incomes to the households. Firm locations are assumed to be fixed throughout the model simulations.[14]

The main model is composed of three submodules (Figure 4.2):

1) **Macroeconomic Model** represents the decision-making process of households to choose the bundle of consumption goods and housing providing the maximum utility and of firms to decide on a bundle of factors with the minimum cost. Hence, the macroeconomic model computes the equilibrium levels of main macroeconomic variables (demand/supply, market prices, factor utilisation). The model takes households' locational/spatial distribution as exogenous input from the output of the Household Choice Model and travel cost input from the output of the Transport Model.

---

[14] Government, property owners or any other decision makers such as real estate developers are neglected in the model.

2) **Household Choice Model** calculates MNL probabilities of selecting specific residential locations and transport modes for households. The model takes household demands for aggregate consumption and housing as exogenous inputs from the output of the Macroeconomic Model and each household's optimized travel time data as input from the Transport Model.
3) **Transport Model** calculates optimized travel time and travel cost required for private car journeys between relevant OD (origin-destination) pairs[15]. It takes households' locational/spatial distribution data from the Household Choice Model.

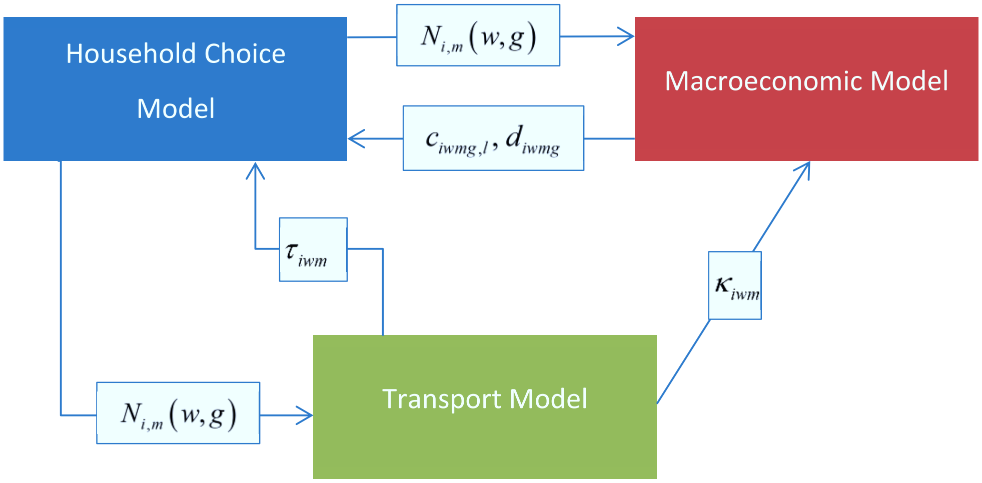


Figure 4.2 Model Overview

The primary data source for the model is London Travel Demand Survey (LTDS) 2014, which provides micro-level information about households and the trips they do in a day. Treatment of data and resulting datasets to be used in the model are explained in detail in the following section.

This section is an introduction to the modelling framework for evaluating impacts of transport policies to be applied in London. Section 4.2 provides detailed information on data to be used in the model and the key attributes. It also provides a spatial synopsis of some findings and implications at boroughs level that are important to have some insight on potential impacts of different scenarios. Section 4.3 is the

---

[15] Travel time and cost of public transport journeys are assumed to remain unchanged and provided to the model as static tables.

model specification section. It explains the network structure, the submodules in the model and equilibrium conditions. Section 4.4 analyses the impacts of the Crossrail 2 project owing to resulting travel savings and provides results in changes in rental prices, modal split, household spatial distribution and private transport travel times. Section 4.5 discusses the main findings.

4.2 Data

4.2.1 Description and Treatment of Data

Primary and secondary data sources for the key attributes of "households table" as well as the transport related variables are summarised in Table 4.1.[16]

Table 4.1 Key data attributes and sources

Household (residential location postcode)	London Travel Demand Survey (LTDS) 2014
Household (working location postcode)	LTDS 2014
Household (travel mode)	LTDS 2014
Household (income)	LTDS 2014
Household type	LTDS 2014 (income), Census 2011 (QS611EW)
Household commuting time (min)	LTDS 2014, Google Maps (for correction)
Household commuting distance (km)	LTDS 2014, Google Maps (for correction)
Household number	LTDS 2014, Census 2011 KS101EW (for boundaries)
House rental rates	Valuation Office Agency (VOA) Private Rental Market Statistics (2014)
Housing expenditures (rooms)	Census 2011 (QS407EW)
Travel cost (private transport)	Travel times, additional cost assumptions (congestion charge, parking, etc.)
Travel cost (public transport)	Transport for London (TfL) Oyster Card Prices (2014)

---

[16] See Appendix H for key statistical information for London.

4.2.1.1 Key attributes of LTDS 2014

The major data source in this Thesis is the Transport for London (TfL) London Travel Demand Survey (LTDS, 2014). In LTDS 2014, there are 3,436,927 households (including ones travelling from out of London) with 8,190 different household categories.

In order to construct a consistent and workable dataset for the application of the numerical methodology, the data from sources described in Table 4.1 (and briefly introduced in Appendix G) is further compiled through the following procedures.

4.2.1.2 Household locations

LTDS (2014) uses the first digits of the postcodes (for example EC2Y from City of London borough) for locations. Postcodes are aggregated to 33 local authorities (boroughs). In case of a postcode is shared by different local authorities (for example, BR1 is used by Bromley, Lambeth and Lewisham) households are distributed among local authorities using special weights indicating shares of local authorities in the postcode. In order to calculate these weights, first, full postcodes (for example EC2Y 8DR from City of London borough) are mapped with 2011 Output Areas (for example, E00000001[17]) with the usual resident population using the Table KS101EW of the Census 2011. Then, full postcodes are aggregated to the first digits to find the shares of output areas in the aggregated postcodes. For the postcodes shared by different boroughs, the total share of output areas from each borough represents the share of the borough in each postcode.

4.2.1.3 Household (income) groups

Data on household income level is divided into 10 original categories in LTDS. I have further aggregated these categories into household groups with respect to income brackets (AB: high income, C: middle income, DE: low income). In the aggregation procedure, social grade approximation percentages from Census 2011 (Table QS611EW) are used for estimating number of households in each group for each borough.

---

[17] To give an opinion on the size of 2011 Output Areas, E00000001 has 194 usual residents according to the Census 2011.

Aggregating procedure to define income levels of household groups deserves a few more sentences. As I explained above, LTDS data provides different income categories for each 8,190-household category. Considering the main the determinants of household income levels are working sector and the skills, income levels in the data are aggregated with respect to the commuting destination and income group of households. This means that households in a household income group with the same commuting destination have the same income level, even if they have different residential location or commuting mode. By this way, 99 income levels (33 working locations * 3 household groups) are estimated. Then, the household table is fed by these income levels. An important benefit of this assumption is the provided robustness of data integrity after the shocks in simulations. Recalling model specifications in Chapter 2, it's assumed that working locations and household (income) groups remain fixed, but residential locations and commuting mode may change. This means that because the number of households with a specific working location and household groups in the economy stays constant throughout the analyses, the total generated income to be split among all the households will remain constant even after household relocations. By doing this, there is no need to define additional parameters to ensure data integrity in simulation analyses.

4.2.1.4 Household commuting

Households generate approximately 1,350,000 commuting trips (one-way) every day. I make two important assumptions to identify household commuting trips:

1) I consider only commuting trips starting and ending in the Great London Area (GLA) boundaries.
2) Each household generates only one commuting trip. I assume that this trip is the longest one in the household data I observe, as the longest trip is the critical one for household location choice problem owing to its magnitudes of travel time and cost.

One important impact of the second assumption is the reduction of commuting modes to motorised transport, as the longest trip of a household often requires using private cars or public transport.

There are four different categories for the preferred commuting mode in LTDS. These categories are walking (0), private transport (1), public transport (2) and other modes (3). Because of the above assumption, shares of walking (0) and other modes (3) in all modes become relatively small[18] when compared to private transport and public transport. Therefore, I merge these two modes with public transport (2). This makes two broad commuting categories: (i) private transport and (ii) public transport. These categories are used for commuting modes in the analyses throughout this chapter. Travel attributes (commuting time, commuting distance) are revised accordingly.

The aggregation procedure described above leads to 866,295 households of the LTDS to be represented in 6,534 different categories defined with four indices.

4.2.1.5 Household expenditures

Households are assumed not to make any saving but to use all their budget for housing, travelling and buying goods. Because there is no saving and the model is static, I assume that households consume a composite good expending the remaining budget from housing and travelling.

Housing Expenditures: Valuation Office Agency's Private Rental Market Statistics (2014) is the primary source for calculating rental rate per household space (rooms including kitchens, living rooms, utility rooms, bedrooms, studies and conservatories) for each borough. LTDS (2014) doesn't give information about total housing expenditures and/or number of spaces that are used by households. For this reason, Census 2011 QS407EW (Number of rooms) data, which gives average number of rooms per household in each borough, is used to make estimations on household spaces used by different household categories. Based on the average numbers and pre-determined caps for each household income group[19], number of rooms are calculated.

---

[18] Share of walking (0) is 11 per cent and share of other modes (3) is 0 per cent.

[19] Housing expenditure cannot exceed 70 per cent of household income for low-income group (DE), 50 per cent for middle income (C) and 30 per cent for high income (AB).

Travel Expenditures: Travel times in the model are calibrated using actual travel times and distances using Google Maps data[20]. Each journey is assumed to start and end at points representing borough centres.

For private transport, fuel consumption per distance is assumed to increase due to increasing level of traffic congestion. This effect is modelled using the following linear interpolation equation, assuming fuel consumption increases linearly between two reference points. Assuming households also travel in non-working days for other purposes, any commuter makes 730 journeys in a year, twice a day and 365 days a year. Reference constant values for fuel consumption and travel times are adopted from Treiber et al. (2008). These values may be replaced by any others from other empirical studies.

$$\kappa_{iw'1'} = \left[C^f + \frac{\tau_{iw'1'}}{\tau^f_{iw'1'}} \frac{t^f_{100}}{t^c_{100}} \left(C^c - C^f \right) \right] \cdot D_{iw} \cdot p^f \cdot \left(\frac{2 \cdot 365}{100} \right) \tag{1}$$

where, C^f is the fuel consumption under no traffic congestion condition (8.24 l/100 km), C^c is the fuel consumption under a reference congestion level that's observed in Treiber et al. (2008), $\tau^f_{iw'1'}$ is the travel time under no congestion condition, t^f_{100} is the reference travel time under no congestion condition (0.963 hour/100 km), t^c_{100} is the reference travel time under a reference traffic congestion level (3.93 hour/100 km), D_{iw} is the distance between borough *i* and borough *w*, and p^f is the fuel cost (average price of petrol is assumed to be 1.25 pound/l in 2014).

I incur flat rate additional costs to total annual private car transport costs, 1000 pounds for journeys to the outside of the congestion charging zone and 2000 pounds for journeys to the inside.

For public transport users, annual travel cost is assumed to be equal to the yearly price of travel card (Oyster Card). Travel zones for origin and destination pairs and connections through central zones are considered when calculating travel card prices.

---

[20] Please note that travel times and distances are aggregated figures with respect to OD pairs.

Composite Good Expenditures: Due to the no saving condition, household expenditure for composite good is equal to the rest of the household income that is left after expenditures on housing and commuting.

Table 4.2 presents the tables that are used in the model and their attributes entering the model as inputs. Based on the data and data organisation and manipulation procedures I explained above, I have created 5 different tables to be used in the model.

Table 4.2 Model Tables and Attributes

Household Table	**Rents Table**	**Income Table**
- Location: o Residential o Working - Household group - Commuting mode - Count (household number) - Expenditure: o Room number o Composite good	- Location - Annual rental rate (room)	- Location (working) - Household group - Annual income
Transport Table	**Origin-Destination (OD) Matrix**	
- Location: o Residential o Working - Distance (km) - Private car parameters: o Time (congested) o Time (free flow) o Annual transport cost - Public transport parameters: o Time o Annual transport cost	Private car users: - Location: o Residential o Working - Count (household number)	

4.2.2 A Spatial Synopsis of the Data

Aggregating data with respect to relevant indices (residential locations, working locations, commuting modes, household groups) would lead to following key numbers:

1) Number of households (commuting): 866,295

    a. Household type (AB): 249,187
    b. Household type (C): 419,100
    c. Household type (DE): 198,008
2) Number of household categories: 6,534
3) The share of private transport users: 33 per cent
4) The share of public transport users: 67 per cent

Based on the above numbers and the following figures (Figures 4.3-4.10), I may come up with some important findings and implications at boroughs level. These are worthy of note to understand the context, so to have some insight on potential impacts of different scenarios.

Figure 4.3 and Figure 4.4 imply central boroughs are attracting working population while outer boroughs are attracting residents. This can be easily attributed to the distribution of available jobs and housing for households in different boroughs. This is the main factor generating unbalanced mobility between boroughs causing daily peak traffics.

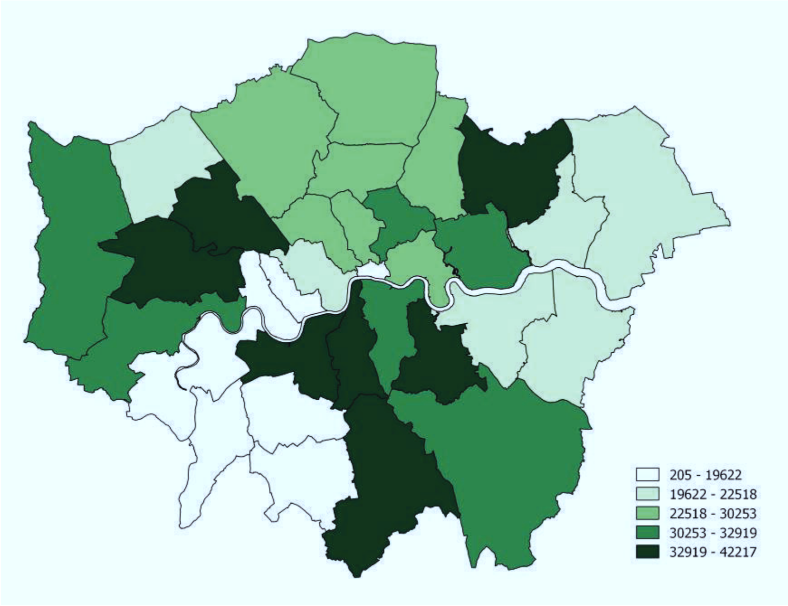


Figure 4.3 Number of Households (Commuting) w.r.t. Housing Locations

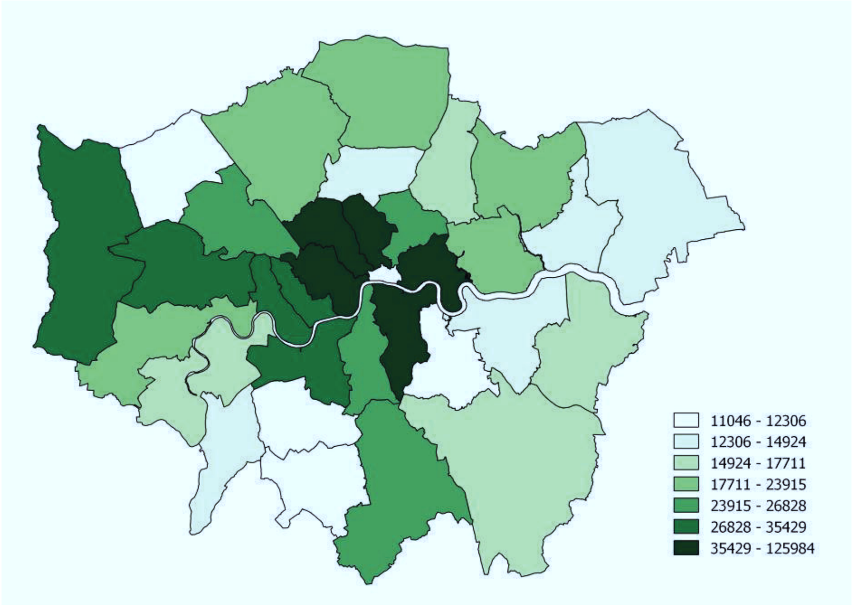


Figure 4.4 Number of Households (Commuting) w.r.t. Working Locations

Figure 4.5 displays the difference in the ratio of working population/residing population in each borough. This ratio is the lowest in Lewisham (0.33) and the highest in City of London (53.88). Other boroughs with the high rates are Westminster (6.10), Camden (2.37), Kensington (1.99) and Tower Hamlets (1.91).

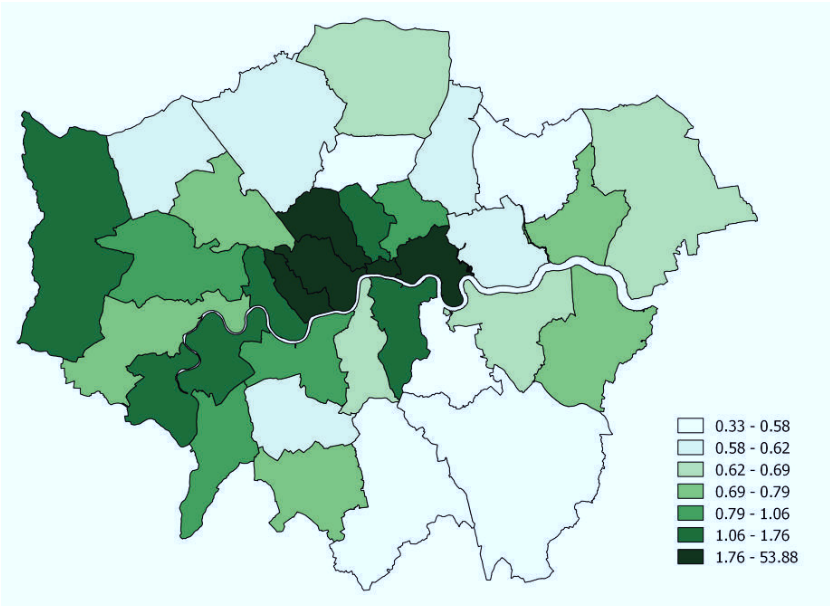


Figure 4.5 Working Population – Residing Population Ratios

Housing prices in central boroughs are higher than the prices in outer boroughs. Housing prices in West London are higher than the prices in East London. (Figure 4.6)

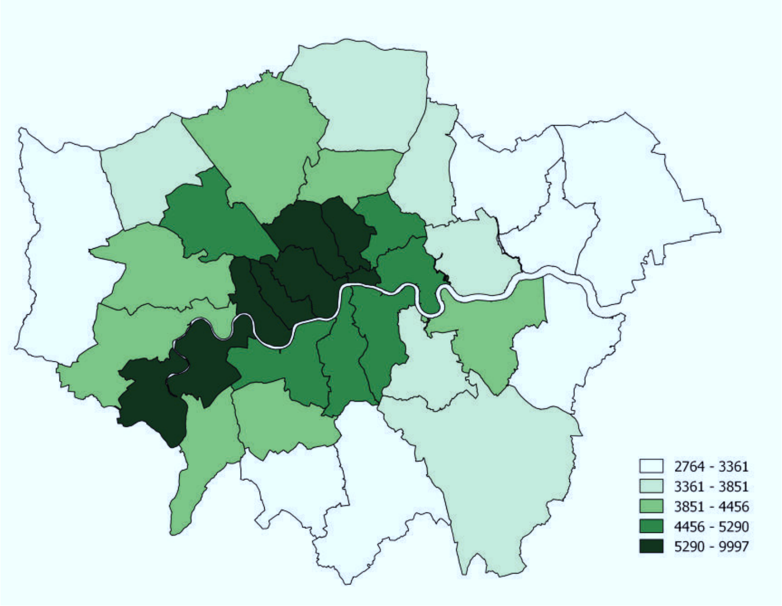


Figure 4.6 Rental Rates (Annual Rate per Room)

Figure 4.7, Figure 4.8 and Figure 4.9 reveal that share of high-income households is substantially high in Centre-West boroughs of London, while the share of low-income households is remarkable in North-East boroughs. The main cause of this heterogeneity is the changing housing prices in boroughs. The similarity in borough colourings in Figure 4.6 (rental rates) and Figure 4.7 (share of high-income households) shows this fact.

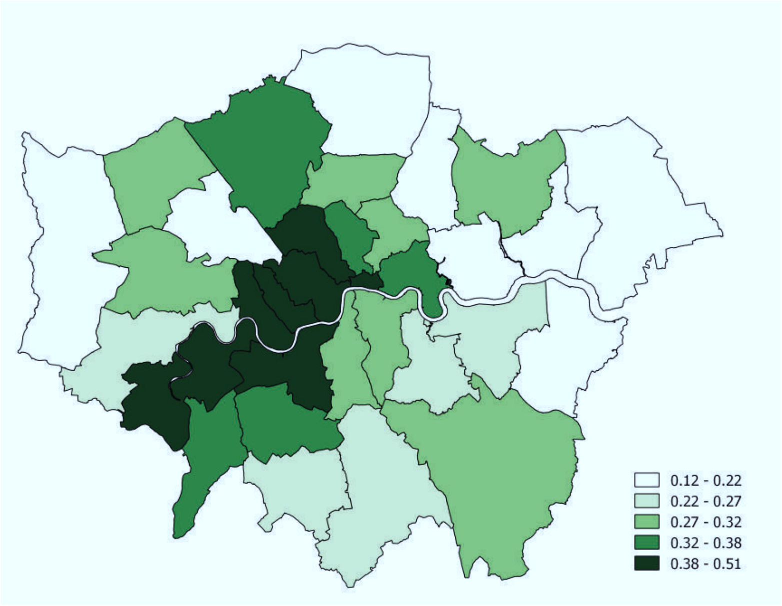


Figure 4.7 Share of High Income Households (AB)

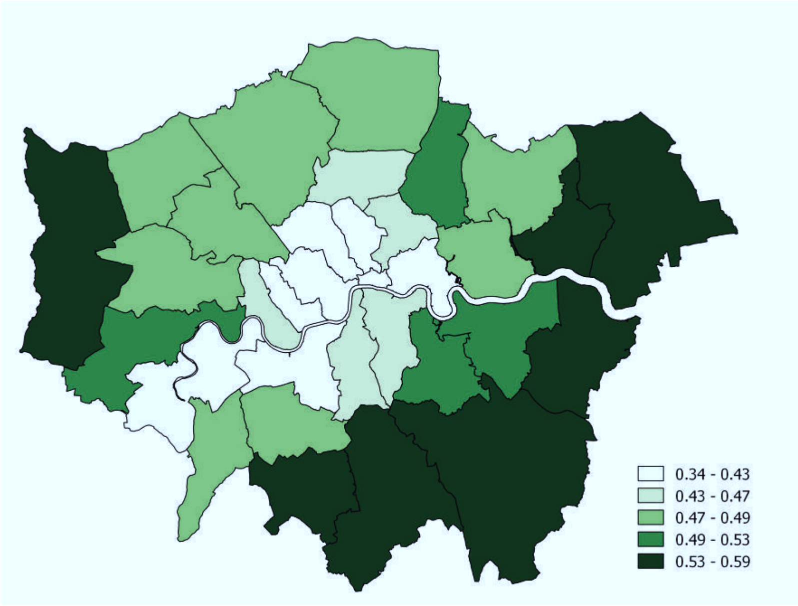


Figure 4.8 Share of Medium Income Households (C)

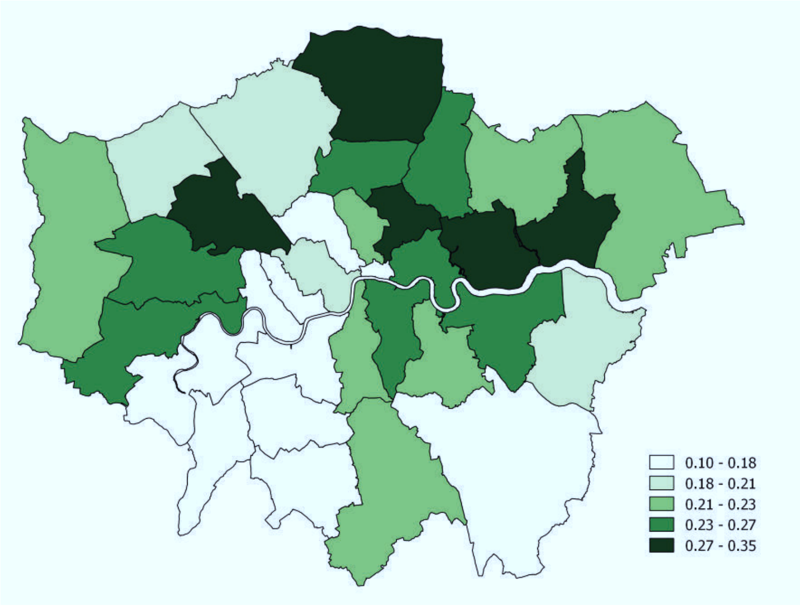


Figure 4.9 Share of Low-Income Households (DE)

Figure 4.10 and Figure 4.11 imply that the dominant transport mode for commuting trips in London is public transport. Car utilisation rates are lower in central boroughs when compared to the outer:

a. The highest car utilisation rates are in Havering (61 per cent), Bexley (55 per cent), Barking and Dagenham (54 per cent), Kingston upon Thames (52 per cent) and Croydon (45 per cent).

b. The lowest car utilisation rates are in Westminster (14 per cent), Tower Hamlets (14 per cent), Lambeth (18 per cent), Camden (15 per cent) and City of London (16 per cent).

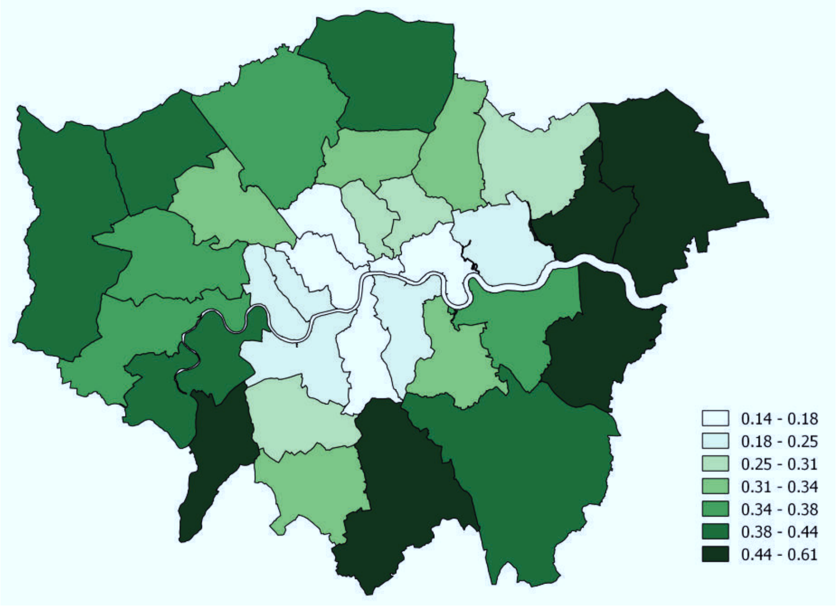


Figure 4.10 Share of Private Transport in Commuting

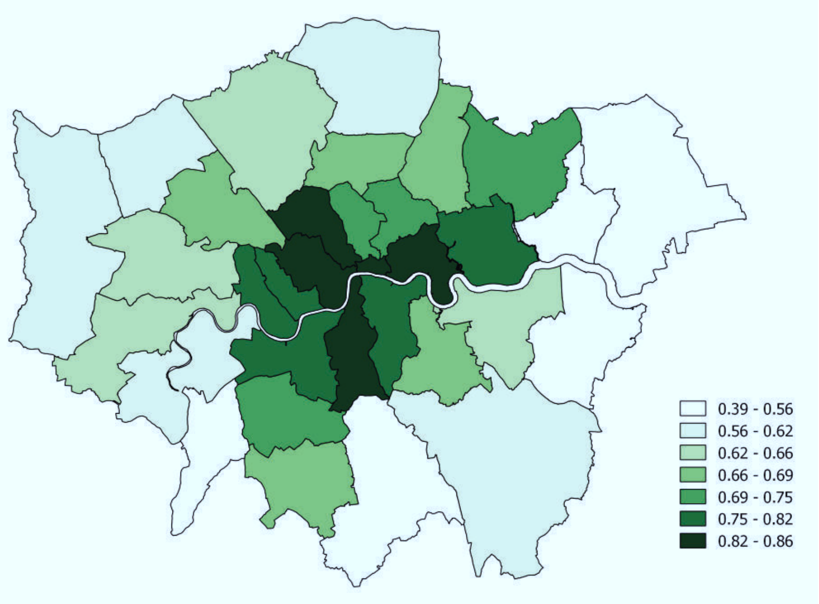


Figure 4.11 Share of Public Transport Users

Above findings imply that private car utilisation is not an income issue but public transport accessibility of boroughs. The share of public transport users is higher in central boroughs where the share of high-income households is the highest. It should also be noted that housing rates are higher in these boroughs as well. There is an obvious tendency among households to live close to the central London. However, high prices owing to the limited housing capacity would force households to live in outer boroughs, in which housing prices are lower, for the sake of bearing travel time and cost.

4.3 Model Specifications

4.3.1 Network Structure

I have created a road network considering travel times and distances between centre points of local authorities. Let $L = \{1, 2, ..., 33\}$ denotes the set of locations, $A = \{1, 2, ..., 170\}$ denotes the set of links connecting population-weighted centroids of local authorities and let $P = \{1, 2, 3\}$ denote the alternative paths for journeys (maximum number of alternative paths is three for this network, the number is to be adjusted for another network). The general network structure of the geographical unit analysed in this Thesis, London is presented in Figure 4.12. Each red dot in the figure denotes the population-weighted centroids of each of the local authority (each represented with 3-letters in the figure). The arcs between red dots are the direct links connecting local authorities in London.

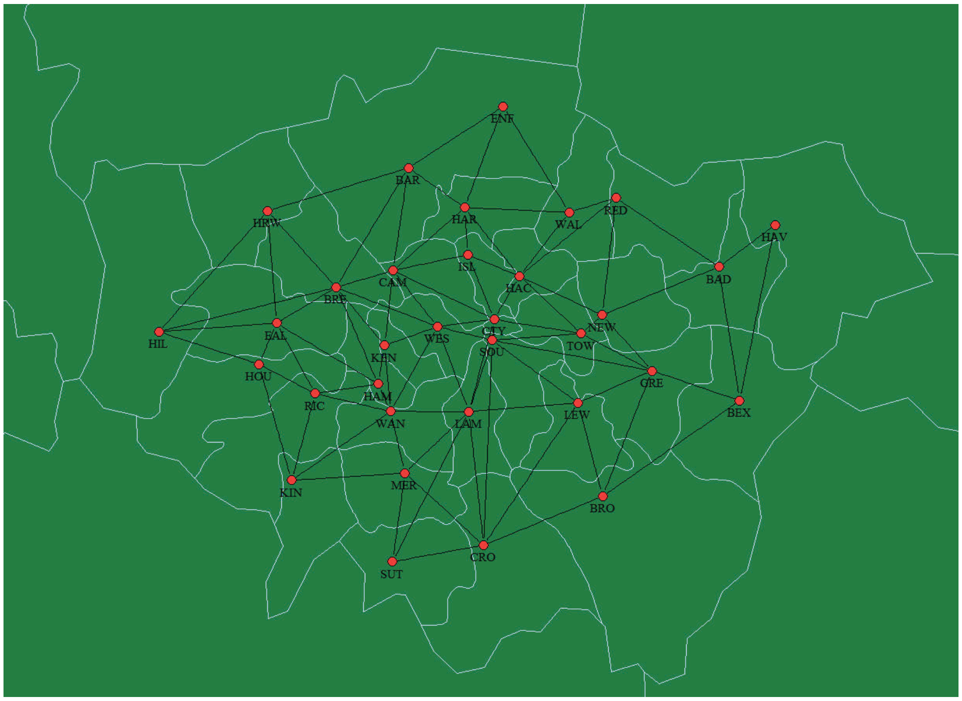


Figure 4.12 London road network

4.3.2 Travel Model

The travel model is a set of equations that are explained in Chapter 2. It calculates private transport travel time and travel costs for each journey between OD pairs. Based on the road network generated, the travel model developed is of Wardropian user equilibrium tradition. In accordance with the model, travel time is calculated using the following set of equations:

(1) Sum of different OD journeys (from location *i* to location *w*) using a link (or arc) within a path equals to the total number of vehicles using that link:

$$q(arc) = \sum_{i \in L} \sum_{w \in L} \sum_{path \in P} \Delta(i, w, path, arc) f(i, w, path), \forall arc \in A \tag{2}$$

where $q(arc)$ is traffic flow on a link, $\Delta(i, w, path, arc)$ is link-path incidence parameter (1 if a link is in a path) and $f(i, w, path)$ is traffic flow on a path for journeys.

(2) Travel time on a link is affected by traffic congestion and is assumed to exhibit following convex increasing function:

$$v(arc) = c_a(arc) + c_b(arc) \left(\frac{q(arc)}{c_k(arc)} \right)^4, \forall arc \in A \tag{3}$$

where, $v(arc)$ is travel time to traverse a link, $c_a(arc)$ is the time required to traverse a link under the no-traffic condition, $c_b(arc)$ is the traffic congestion coefficient and $c_k(arc)$ is the link capacity.

(3) Sum of car OD journeys using different paths equals to the total number of households commuting between these OD pairs:

$$\sum_{path \in P} f(i, w, path) = \sum_{g \in G} N_{i,'1'}(w, g), \forall i, w \in L \tag{4}$$

where, $N_{i,'1'}(w, g)$ is the number households residing at location *i*, commuting to location *w*, with household category *g* and using their private cars for their journeys.

(4) The total travel time of a path (from location *i* to location *w*) equals to the sum of travel times of all links belonging to this path:

$$\tau_{iw'1'}\left(path\right)=\sum_{arc\in A}\Delta(i,w,path,arc)\cdot v(arc),\ \forall i,w\in L,\ \forall path\in P \tag{5}$$

where $\tau_{iw'1'}\left(path\right)$ is the total travel private car time on a path used for journeys from location *i* to location *w.*

(5) For cars (*m*=1), if a path is used for travelling from *i* to *w* travel time of this path will be equal to any path that is used for travelling from *i* to *w* (Wardrop's First Principle):

$$\tau_{iw'1'}\left(path='1'\right)=\sum_{path\in P}\frac{\tau_{iw'1'}\left(path\right)}{\pi\left(i,w\right)},\ \forall i,w\in L \tag{6}$$

where, $\pi\left(i,w\right)$ is the number of different paths used for a journey from location *i* to location *w*. This is maximum three for the defined London network.

So, the travel model solves for the unique optimal solution[21] of the time required for each journey using the specified equations above. This solution becomes the input to the Macroeconomic Model and Household Choice Model.

4.3.3 Households

Households are categorised according to their residential location (*i*), working location (*w*), preferred commuting mode (*m*) and household groups in terms of household income (*g*). For this setting, let *L* denotes the set of locations (and nodes) $L=\{1,2,...,33\}$ including 33 administrative regions (boroughs) in London, *M* denote the set of commuting modes $M=\{1,2\}$ including car (1) and other transport modes (primarily public transport) (2), and *G* denotes the set of household groups $G=\{AB,C,DE\}$ including high-income households (AB), middle-income households (C) and low-income households (DE).

---

[21] See Appendix B for the uniqueness proof.

Households maximise their utilities using a constant-elasticity-of-substitution (CES) utility function. The CES utility function is composed of two types of units: (i) housing and (ii) consumption good, which is a composite good representing any other goods and services (excluding transport) consumed by the consumers (Figure 4.13).

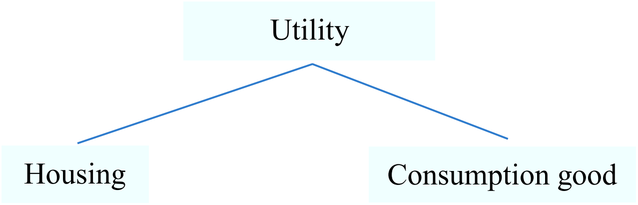


Figure 4.13 CES household utility function

Here, transport cost isn't considered to be part of consumption composite. However, the value of transport services is added to the total production value of the economy[22]. On the other hand, transport is assumed to cause a certain level of "disutility of travelling" owing to the passing time in traffic as explained in Chapter 2. Although transport activity causing disutility is not priced at any market, Household Choice Model takes this effect into account when deciding on a household's decision residential location choice and commuting mode choice[23]. There is no `utility of neighbourhood`, which is introduced in the general model in Chapter 2, in the household utility function in this setting.

Under the framework briefly summarized above, the representative household's utility function takes the form:

$$\begin{gathered}\operatorname*{Max}_{c,d}\left\{U_{iwmg}\left(c,d\right)=\left[\alpha_{iwmg}c_{iwmg}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right]^{1/\rho}-\gamma_{iwmg}\tau_{iwm}\right\} \\ \text{s.t. the budget}:-M_{iwmg}+r_i d_{iwmg}+pc_{iwmg}+\kappa_{iwm}\leq 0,\forall i,w\in L,\forall m\in M,\forall g\in G\end{gathered} \tag{7}$$

where d is the consumption of housing (number of rooms), c is the quantity of consumed composite good, γ is the coefficient for travelling disutility (varying by household type), τ is travel time, M is the total income of a household, r is the rental rate for housing and p is the price for consumption good and κ is travel cost. Note that

---

[22] See later in firm specifications for the treatment of transport services in the economy.

[23] See Anas and Liu (2007) and Anas and Hiramatsu (2013) for constant utility effects of choices.

indices *i*, *w*, *m* and *g* stand for boroughs for residential and working locations, commuting mode and household group, respectively.

The household budget is:

$$M_{iwmg} = w_{wg} + \delta e_{wg}^{K} + \sum_{i'} r_{i'} e_{wg}^{H}\left(i'\right), \forall i \in L, \forall m \in M \tag{8}$$

where e^K and e^H are the household endowments of capital and housing (represented in terms of number of rooms) at a location $i' \in L$.

The Lagrangian of the problem of the household can be stated in the following form:

$$\mathcal{L}\left(d,c,\lambda\right) = \left[\alpha_{iwmg} c_{iwmg}^{\rho} + \alpha_{iwmg}^{h} d_{iwmg}^{\rho}\right]^{1/\rho} - \gamma_{iwmg}\tau_{iwm} + \lambda\left[M_{iwmg} - r_i d_{iwmg} - pc_{iwmg} - \kappa_{iwm}\right] \tag{9}$$

Here, λ is the Lagrange multiplier. Taking the derivatives of the Lagrangian with respect to decision variables *d* and *c*, and the Lagrange multiplier λ leads to the following first-order conditions for the optimizing households, representing demand for housing and composite good:

$$\left(d\right) \quad \alpha_{iwmg}^{h}\left[\alpha_{iwmg} c_{iwmg}^{\rho} + \alpha_{iwmg}^{h} d_{iwmg}^{\rho}\right]^{(1-\rho)/\rho} d_{iwmg}^{\rho-1} - \lambda r_i = 0 \tag{10}$$

$$\left(c\right) \quad \alpha_{iwmg}\left[\alpha_{iwmg} c_{iwmg}^{\rho} + \alpha_{iwmg}^{h} d_{iwmg}^{\rho}\right]^{(1-\rho)/\rho} c_{iwmg}^{\rho-1} - \lambda p = 0 \tag{11}$$

$$\left(\lambda\right) \quad M_{iwmg} - r_i d_{iwmg} - pc_{iwmg} - \kappa_{iwm} = 0 \tag{12}$$

Since $\rho = \frac{\sigma - 1}{\sigma}$ household demand for consumption becomes a function of disposable income and prices. Therefore, associated demand functions can be stated as in the following forms:

$$d_{iwmg} = \left(\frac{\alpha_{iwmg}^{h}}{r_i}\right)^{\sigma} \frac{M_{iwmg} - \kappa_{iwm}}{\left(\alpha_{iwmg}^{h}\right)^{\sigma} r_i^{1-\sigma} + \left(\alpha_{iwmg}\right)^{\sigma} p^{1-\sigma}} \tag{13}$$

$$c_{iwmg} = \left(\frac{\alpha_{iwmg}}{p}\right)^{\sigma} \frac{M_{iwmg} - \kappa_{iwm}}{\left(\alpha_{iwmg}^{h}\right)^{\sigma} r_i^{1-\sigma} + \left(\alpha_{iwmg}\right)^{\sigma} p^{1-\sigma}} \tag{14}$$

Recalling discussions on residential location and mode choices of households in Chapter 1, MNL probability of choosing a residential location and associated travel mode for any household is calculated. Assume that the number of households with household group *g* and working location *w* is exogenously given and $N\left(w,g\right)$. Then, the number of households for each location *i* using commuting mode *m* would be:

$$\begin{aligned} N_{i,m}\left(w,g\right) &= P_{w,g}\left(i,m\right)\cdot N\left(w,g\right) \\ &= \frac{\exp\left[\left(\alpha_{iwmg}c_{iwmg}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right)^{1/\rho}-\gamma_{iwmg}\tau_{iwm}\right]}{\sum_{j\in L}\sum_{m'\in M}\exp\left[\left(\alpha_{jwm'g}c_{jwm'g}^{\rho}+\alpha_{jwm'g}^{h}d_{jwm'g}^{\rho}\right)^{1/\rho}-\gamma_{jwm'g}\tau_{jwm'}\right]}N\left(w,g\right) \end{aligned} \tag{15}$$

4.3.4 Firms

On the production side of the economy, the representative form is assumed to operate under a production function that exhibits a constant-elasticity-of-substitution (CES) form. The motivation of a producer is to minimise the cost for a certain amount of production:

$$\underset{K,L}{\text{Min}}\left\{\delta K+wL\right\} \tag{16}$$

where δ is the rental rate of the factor input capital *K* and *w* is the wage rate paid to the employees for factor input labour *L*.

Deriving the first-order conditions for profit maximization leads to the following factor demand equations:

$$L=\frac{Y}{\phi}\left[\beta^{\sigma}\delta^{1-\sigma}+\left(1-\beta\right)^{\sigma}w^{1-\sigma}\right]^{\frac{\sigma}{1-\sigma}}\left(1-\beta\right)^{\sigma}w^{-\sigma} \tag{17}$$

$$K=\frac{Y}{\phi}\left[\beta^{\sigma}\delta^{1-\sigma}+\left(1-\beta\right)^{\sigma}w^{1-\sigma}\right]^{\frac{\sigma}{1-\sigma}}\beta^{\sigma}\delta^{-\sigma} \tag{18}$$

With total cost function of the production firms expressed as:

$$C\left(\delta,w\right)=\delta K+wL=\frac{Y}{\phi}\left[\beta^{\sigma}\delta^{1-\sigma}+\left(1-\beta\right)^{\sigma}w^{1-\sigma}\right]^{\frac{1}{1-\sigma}} \tag{19}$$

4.3.5 Equilibrium conditions

The macroeconomic equilibrium of the model economy is defined by the following set of conditions:

1) Total production is equal to the sum of households' final consumption on goods and total travel costs:

$$Y = \sum_{i \in L} \sum_{w \in L} \sum_{m \in M} \sum_{g \in G} N_{i,m}(w,g) \left[c_{iwmg} + \kappa_{iwm} / p \right] \tag{20}$$

2) Total factor utilisation cannot exceed initial household endowments:

$$L \leq \sum_{i \in L} \sum_{w \in L} \sum_{m \in M} \sum_{g \in G} N_{i,m}(w,g) \cdot e^{L}_{wg} \tag{21}$$

$$K \leq \sum_{i \in L} \sum_{w \in L} \sum_{m \in M} \sum_{g \in G} N_{i,m}(w,g) \cdot e^{K}_{wg} \tag{22}$$

3) There is no new construction activity and total housing demand of households cannot exceed existing housing stock at each location:

$$\sum_{w \in L} \sum_{m \in M} \sum_{g \in G} N_{i',m}(w,g) \cdot d_{i'wmg} \leq \sum_{i \in L} \sum_{w \in L} \sum_{m \in M} \sum_{g \in G} N_{i,m}(w,g) \cdot e^{H}_{iwmg}(i'), \forall i' \in L \tag{23}$$

4.4 Scenario Analysis: The Impact of an Improvement in Public Transport

In this Section, in order to be able to analyse the effects of public transportation policies on people's decisions on their residential locations, modal split and market prices. I study the Crossrail 2 Project of London. I first provide a general overview of the project in terms of planned routes and improvement in accessibility, and expected outputs and outcomes. Next, I explain briefly how the resulting improvement may be reflected in travel time savings for the journeys between boroughs. Then, I outline the key assumptions in model construction and provide the numerical results of the Crossrail 2 Project in boroughs.

4.4.1 Case Study: Crossrail 2 Project

Crossrail 2 is a new railway project in the North-South direction of London. It will connect National Rail networks in Surrey and Hertfordshire with connections to other rail systems (London Underground, London Overground, Crossrail 1, and other national and international rail services). The planned route is between Wimbledon in the south and Tottenham Hale and New Southgate in the north. The new line will stop at the following stations: (i) Wimbledon, (ii) Balham, (iii) Clapham Junction, (iv) King Road Chelsea, (v) Victoria, (vi) Tottenham Court Road, (vii) Euston St. Pancras, (viii) Angel, (ix) Dalston, (x) Tottenham Hale, (xi) Seven Sisters, (xii) Wood Green (or Turnpike Lane and Alexandra Palace) and (xiii) New Southgate. (Figure 4.14)

The main benefit of the project is substantial travel time savings, particularly for journeys on the North-South axis of London. It’s expected that the Project will help people living in outskirts of London to reach the core of the city more conveniently. Additional travel time savings are expected in well-connected neighbourhoods (particularly central boroughs) owing to increase in the number of trains (capacity increase).

Besides the significant decrease in journey times, the Project is expected to support economic growth. Key outputs and outcomes of the project are expected to be (i) enabling the development of 200,000 new homes, (ii) supporting 60,000 new jobs across the UK supply chain, (iii) supporting 200,000 new jobs once completed, (iv) increasing London’s rail capacity by 10 per cent, (v) at peak times, providing 30 trains per hour to destinations across London, Hertfordshire and Surrey, (vi) bringing 800 stations across the UK within one interchange and (vii) providing additional capacity for up to 270,000 more people to travel into London during peak periods.

The project is expected to be operational in the early 2030s with about 10 years of building phase, which will start in early 2020s. The cost of the Crossrail 2 project is estimated at 27 billion pounds in 2015 prices (Crossrail2, 2018b).

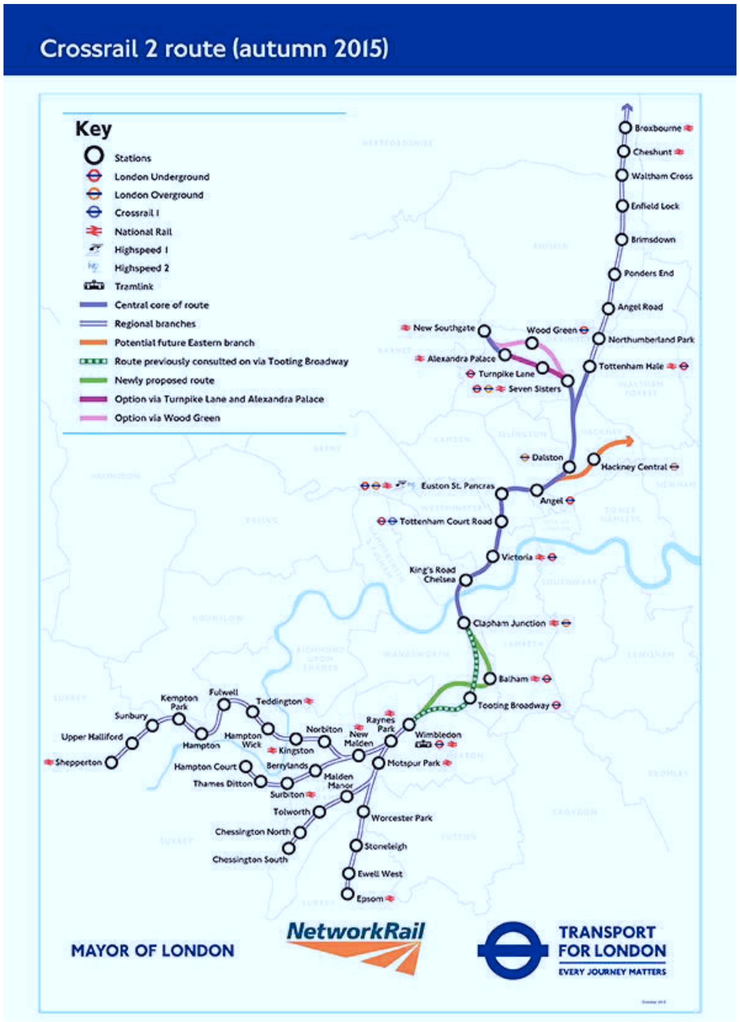


Figure 4.14 Overview of Crossrail 2 Project (Crossrail 2, 2018a)

The estimations on total potential time savings owing to the Crossrail 2 Project is shared with the public on the project website at http://crossrail2.co.uk/discover/regional-national-benefits/. Figure 4.15 illustrates these savings in total generalised minutes terms.

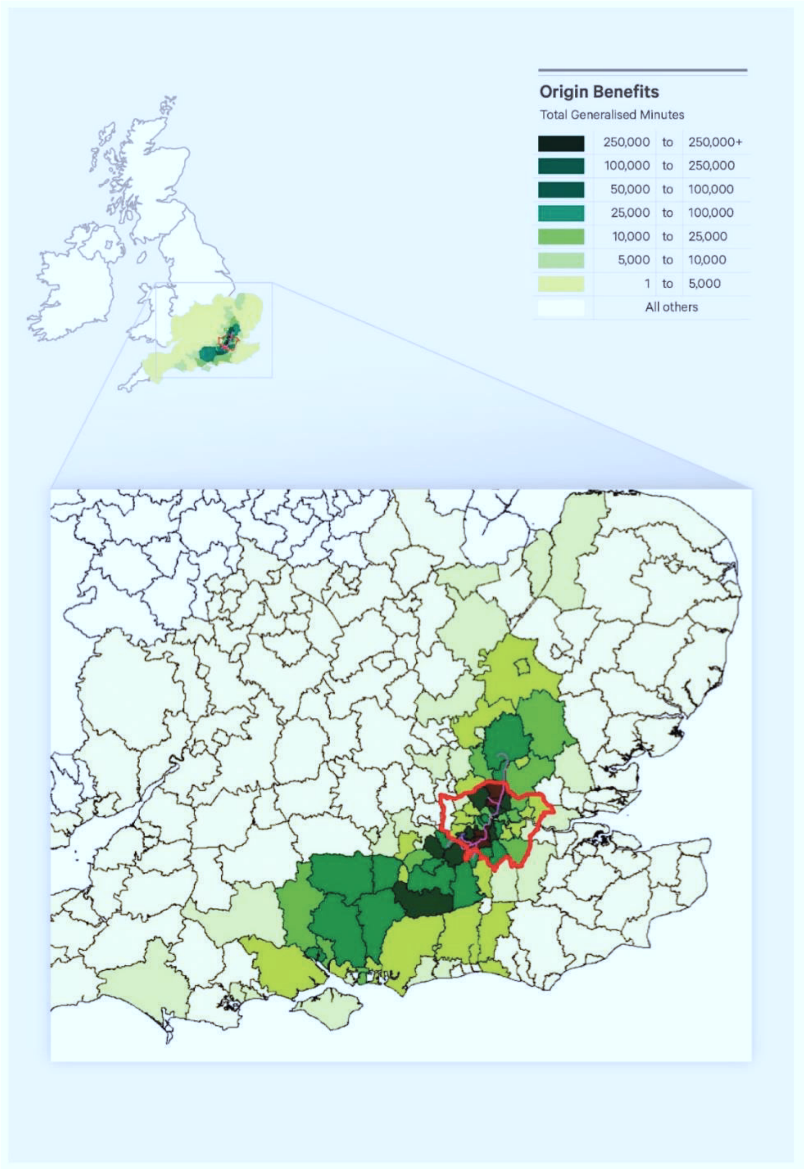


Figure 4.15 Estimated Travel Time Savings of Crossrail 2 (Crossrail 2, 2018c)

However, the scenario analysis demands public transport travel improvement data for each OD pair at borough level. This information is not available as public information. After several attempts to contact the Crossrail 2 Project Team of the Transport for London (TfL), I decided to use Crossrail 2 factsheets that are available on the `consultations` page of the TfL website[24]. Using the figures related to travel time savings, I generated a travel time-saving matrix. Please note that these values are

---

[24] TfL (2015) https://consultations.tfl.gov.uk/crossrail2/october2015/#Crossrail 2 Factsheets

not official travel time savings but estimations. Appendix I explains this estimation procedure and provides the complete list of public transport travel time savings.

According to these estimations, the boroughs with the highest travel time savings are: (i) Kingston upon Thames, (ii) Barnet, (iii) Enfield, (iv) Haringey and (v) Merton.

4.4.2 Underlying Assumptions

The scenario (shock) is implementing Crossrail 2 Project, which is a public transport project. As previously explained, the Project improves public transport capacity by providing a new line on the North-South axis of London and increasing the number of trains. The implementation of the shock takes the form of improvement in public transport journey times and does not consider the expected transport improvements from the other on-going public transport projects (Crossrail 1 Project[25], in particular).

That I evaluate the impacts of accessibility change is the key assumption of this scenario analysis. I neglect the impacts of investment expenditures.

In addition to the model assumptions that are described in Section 4.3 for model specifications, I also assume that housing stock stays constant due to the assumption of no real estate development activity in the economy. So, existing housing stock is split among households after the shock and any change in housing demand will be reflected in a change in housing prices under certain conditions.

Public transport cost is also assumed to remain unchanged after the implementation of the Crossrail 2 project.

4.4.3 Simulation Results

I present and discuss the results, especially paying attention to the reaction of the following variables to the shock implemented: (i) change in housing rental prices,

---

[25] Crossrail 1 (or Crossrail in more common terms) Project is a railway project connecting Reading and Heathrow in the west with Shenfield and Abbey Wood in the east.

(ii) change in modal split, (iii) change in household spatial distribution and (iv) change in private transport travel time.

As expected, simulation results show that public transport improvement would have a substantial impact on people's relocation decisions. This leads to remarkable changes in household spatial distribution favouring boroughs benefiting the most from the capacity increase of the Crossrail 2. The resulting increase in demand for these boroughs leads to relative price increases in the housing market.

Results imply that the Crossrail 2 project would change a substantial number of people's decisions to shift from private transport to public transport. This is an important result and consistent with the expectations of the Project. Accordingly, the modal shift from private transport to public transport would result in a certain level of traffic congestion relief in some routes. However, the share of public transport drops in some boroughs. The primary cause of this change is the relocation of private transport users to the other boroughs where public transport improvement is limited.

Another major impact is observed in household spatial distribution. Model results show that the number of households in central boroughs of London decreases substantially owing to public transport accessibility improvement. This is an expected result and explained in detail later in this section.

4.4.3.1 Rental prices

Model results show that the shock would lead to price increases in some areas. These with the highest rates are: (i) City of London (11.59 per cent), (ii) Waltham Forest (8.81 per cent), (iii) Barnet (8.76 per cent), (iv) Merton (7.36 per cent), (v) Kingston upon Thames (7.26 per cent), (vi) Hounslow (6.63 per cent), (vii) Sutton (4.56 per cent) and (viii) Enfield (3.11 per cent).

The remarkable change in City of London and Hounslow rental prices shows that some of the observed impacts on the housing prices cannot be solely explained by the changes in the transport accessibility owing to the public transport improvement. It is the major cause triggering some kinds of household movements, though.

Starting with City of London, first, this borough is in the very centre of London with a good public transport connectivity. So, it -like other central boroughs- benefits from any public transport improvement at this scale. Indeed, when we look at the details, results show that housing demand increase is primarily caused by the households using (already using or shifting) public transport. In City of London, the share of private transport in modal split drops from 15.39 per cent to 12.71 per cent.

Second, as illustrated in Figure 4.16 (shades of red represent price decreases while shades of green do increases), City of London is surrounded by boroughs suffering from rental price decreases. This might be a signal for household movement from these boroughs to City of London. When we go further into details, we see that increase of the number of middle-income households is remarkably disproportionate when compared to increases in numbers of different groups of households. Although high-income households are the largest group (62 per cent before shock) in City of London, increase in the number of this group is limited (two households) while the number of middle income and low-income households increase by eleven and four, respectively. The underlying cause of this outperformance might be the initial housing price formation. Housing rents in City of London are lower when compared to neighbouring central boroughs like Kensington and Chelsea, and Westminster. Annual room rents in Kensington and Chelsea, and Westminster is 9,997 pounds and 8,910 pounds, respectively, while it is 7,620 pounds in City of London.

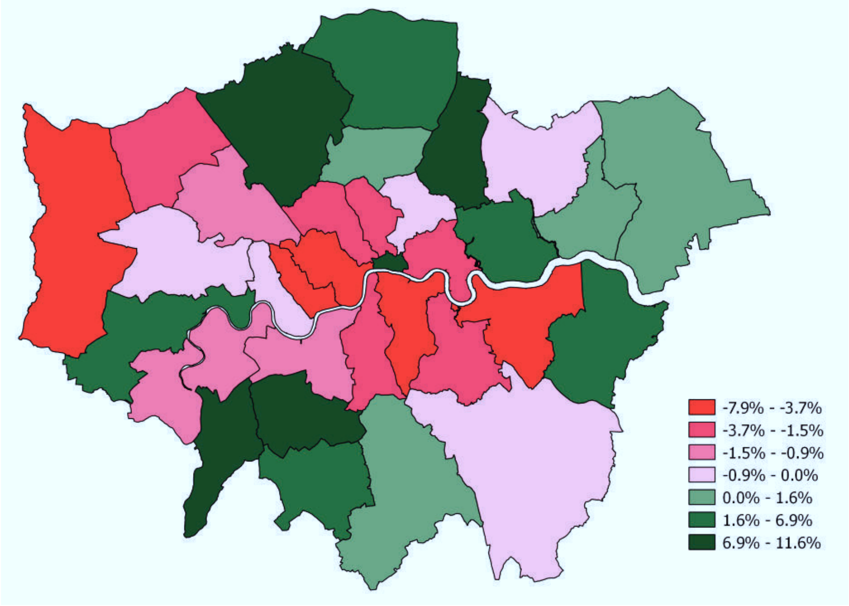


Figure 4.16 Percentage Change in Housing Rental Prices

Third, City of London, compared to the other boroughs, is very small in scale (143 commuting households). Therefore any (seemingly insignificant change in total but significant for the borough) change in the number of households has a substantial impact on housing prices[26].

Turning to Hounslow, there is a different story. After implementing Crossrail 2 project, the number of households in Hounslow increases by 4.14 per cent, which is lower than housing price increase (6.63 per cent). Household increase in Hounslow is primarily caused by an increase in the high-income household group (AB). The share of this group in household number increase is more than 88 per cent. This shows that Hounslow succeeds to attract high-income households leaving Central London. Another consequence of this relocation is the remarkable change in modal split favouring private transport in Hounslow. The share of private transport increases from 37.57 per cent to 44.76 per cent. This is also fed by high-income private transport users. The number of high-income private transport users increases by 62 per cent.

Leaving two above boroughs aside, accessibility improvement owing to Crossrail 2 project leads to price increases in certain boroughs as expected. There are significant price impacts in Merton, Barnet, Kingston upon Thames, Waltham Forest, Sutton and Enfield, at which the Crossrail 2 project offers substantial accessibility improvements.

As the number of households is fixed in analyses, and so boroughs are competing to attract households from a pool with a fixed number of households, the shock leads to decreases in the price of housing services in some boroughs. These boroughs are: (i) Kensington and Chelsea (-7.88 per cent), (ii) Greenwich (-7.27 per cent), (iii) Hillingdon (-6.97 per cent), (iv) Southwark (-6.52 per cent) and (v) Westminster (-3.93 per cent). These boroughs are particularly in Central London. These price changes may be attributed to the decay in relative advantage of central boroughs in terms of public transport accessibility owing to the Crossrail 2 project. Because of high housing prices, these boroughs would lose their household demands in the housing to the other boroughs with lower prices coupled with improved public

---

[26] In this case, total number of households in City of London increases by 17. Although this increase is low, it makes a 12 per cent increase. In order to increase the accuracy, this borough may be merged with another borough (e.g. Westminster) in analyses.

transport accessibility. There is an exception in this list. It is Hillingdon, which is one of the boroughs benefiting the least from the public transport improvement due to the Crossrail 2 project. (Figure 4.16)

4.4.3.2 Modal split

As expected, the shock, which is an improvement in the public transport system, increases the share of public transport use for commuting purposes. The share of public transport increases remarkably from 67.27 per cent to 71.00 per cent in total London, increasing the number of public transport users by 32,280. Boroughs with the highest change in public transport use are: (i) Kingston upon Thames (23.51 per cent), (ii) Haringey (23.47 per cent), (iii) Merton (22.77 per cent), (iv) Waltham Forest (22.36 per cent) and (v) Sutton (17.98 per cent). (Figure 4.17)

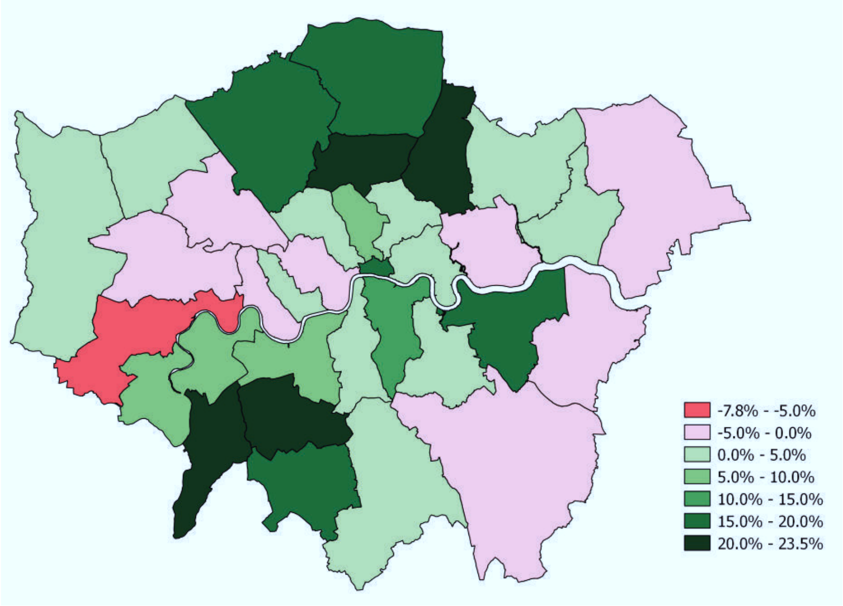


Figure 4.17 Percentage Change in Public Transport Use

These results are well in line with the expectations on the Crossrail 2 improvements in public transport accessibility. Public transport use increases in boroughs on the North-South axis where the Crossrail 2 provides public transport improvement, while the share of private transport users increases in some boroughs in the East-West axis increases[27][28]. There are two possible causes of this fact: (i) modal shift from public transport to private transport owing to traffic congestion relief after implementing the Crossrail 2 and (ii) location shift (not modal shift) of private transport users to the other boroughs where public transport improvement is limited. The impact of the latter would be greater than the first one. Recalling the Hounslow case in the previous section, there was a substantial household increase in this borough primarily owing to the movement of high-income households. When we go further details in the data, it's seen that this increase is caused by private transport users. Therefore, after implementing the Crossrail 2 project, Hounslow becomes an attraction area for high income (AB) and middle income (C) households using private transport for commuting purpose. (Table 4.3)

Table 4.3 Household Distribution in Hounslow

	Before Shock		**After Shock**		**Change Rate**	
HH Group/Travel Mode	**Private**	**Public**	**Private**	**Public**	**Private**	**Public**
High income (AB)	2,309	5,403	3,744	5,080	62.15%	-5.98%
Middle income (C)	5,960	9,402	7,367	8,012	23.61%	-14.78%
Low income (DE)	3,137	4,149	3,041	4,375	-3.06%	5.45%

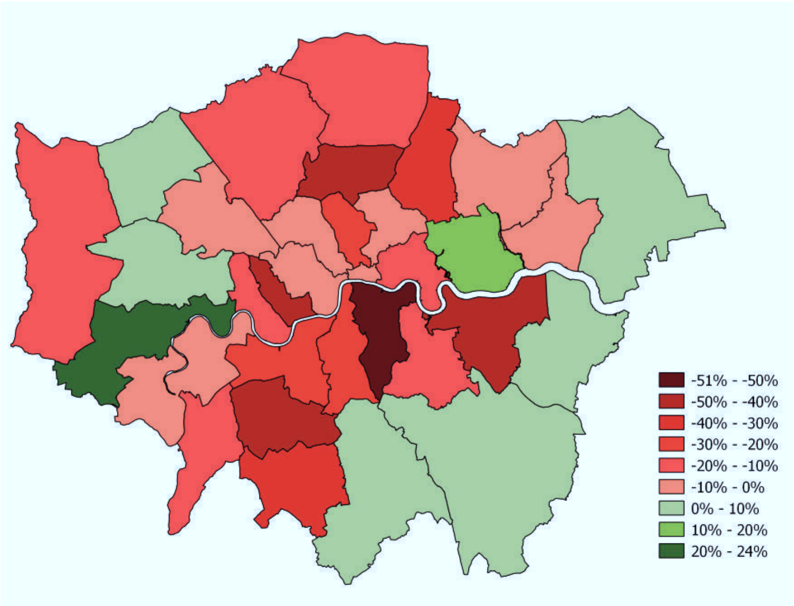


Figure 4.18 Percentage Change in Private Transport Use

---

[27] Please recall that the Crossrail 1 project is not considered, as previously mentioned.

[28] Number of public transport users in Hounslow drops by 7.85 per cent.

As expected, the number of private transport users drops in most boroughs. Among few exceptions, Hounslow and Newham come to the fore. (Figure 4.18) Recalling the mechanism having an impact on after-shock modal split formation in Hounslow, there is a similar mechanism working in Newham, as well. Like Hounslow, Newham becomes an attraction centre for private transport users (but with a smaller scale compared to Hounslow) after implementing the Crossrail 2 project. (Table 4.4) Recalling Figure 4.16 on housing rental price changes, Newham is one of the few boroughs with limited public transport accessibility but enjoying considerable housing price increase. Housing prices in Newham increase by 1.66 per cent after implementing the Crossrail 2 project.

Table 4.4 Household Distribution in Newham

	Before Shock		**After Shock**		**Change Rate**	
HH Group/Travel Mode	**Private**	**Public**	**Private**	**Public**	**Private**	**Public**
High income (AB)	1,072	4,278	1,366	4,265	27.43%	-0.30%
Middle income (C)	4,919	10,769	5,472	10,528	11.24%	-2.24%
Low income (DE)	3	11,374	26	10,963	766.67%	-3.61%

Figure 4.19 displays change in share of public transport in modal split. To give an example, the share of public transport (for commuting) in Hounslow drops by 7.19 per cent from 62.43 per cent to 55.24 per cent. Shares of public transport in Haringey and Merton increase by 15.14 per cent and 15.05 per cent respectively. It’s seen that share of public transport drops in all outer boroughs in South-East London (Croydon, Bromley, Bexley and Havering).

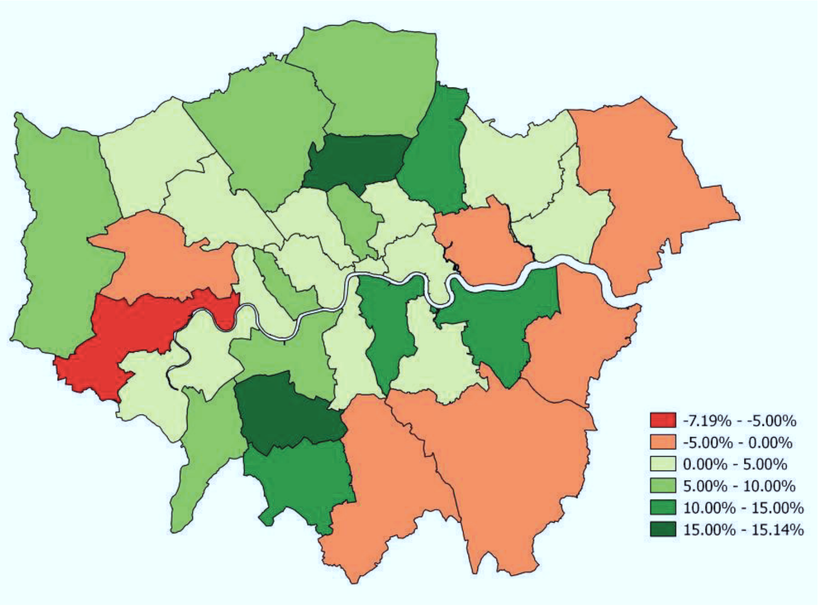


Figure 4.19 Change in Share of Public Transport

Another borough with a decreasing share of public transport in the modal split is Ealing in West London. Table 4.5 displays that the numbers of high income and middle-income private transport users increase while numbers of low-income private transport users and public transport users from all groups decrease. This change is like the change in the neighbouring borough of Hounslow that is explained above. The exception is that number of low-income public transport users drops, as well. The net household number change is negative (-181) in Ealing.

Table 4.5 Household Distribution in Ealing

	Before Shock		**After Shock**		**Change Rate**	
HH Group/Travel Mode	**Private**	**Public**	**Private**	**Public**	**Private**	**Public**
High income (AB)	4,742	5,362	4,765	5,328	0.49%	-0.63%
Middle income (C)	6,024	11,269	6,144	11,247	1.99%	-0.20%
Low income (DE)	2,519	6,037	2,386	5,902	-5.28%	-2.24%

4.4.3.3 Household spatial distribution

As the total number of (commuting) households is assumed to be fixed, the results of the analysis should be discussed in the constraints of the assumption; therefore, allows one to comment on the relocation of the existing households.

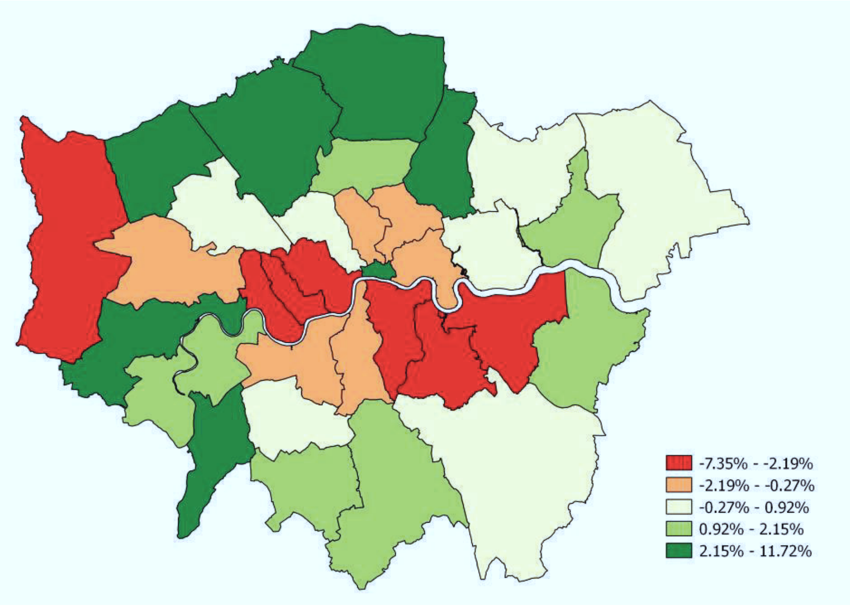


Figure 4.20 Change in Household Spatial Distribution

The results show that Barnet and Waltham Forest are the two boroughs attracting a significant number of households. Barnet attracts 1,949 additional households (6.46 per cent increase in the number of households) and Waltham Forest attracts 1,591 (5.94 per cent increase in the number of households) after implementing the Crossrail 2 project. These results are expected, as these boroughs are among the boroughs enjoying public transport accessibility improvement the most. (Figure 4.20)

Boroughs with the highest percentage increase in number of households are: (i) City of London (11.72 per cent), (ii) Barnet (6.46 per cent), (iii) Waltham Forest (5.94 per cent), (iv) Hounslow (4.14 per cent), (v) Kingston upon Thames (3.43 per cent), (vi) Enfield (3.05 per cent) and (vii) Harrow (2.40 per cent). Among the exceptional cases[29] in these boroughs, the mechanism behind household number increases in City of London and Hounslow.

Turning to Harrow, which benefits very little from the public transport improvement due to the Crossrail 2 project (Figure 4.16), housing prices in this borough drops by 1.52 per cent. This can be attributed to the change in household group composition in Harrow. This means that although the number of households

---

[29] The term exceptional case refers to the case where public transport accessibility improvement is not the direct cause of change.

residing in this borough increases, household space demand drops due to now lower residential demand of incoming households. The number of high income (AB) households drops by 742 from 6,626 to 5,884 while numbers of middle income (C) and low income (DE) households increase by 285 and 951, respectively. (Table 4.6)

Table 4.6 Household Distribution in Harrow

	Before Shock		**After Shock**		**Change Rate**	
HH Group/Travel Mode	**Private**	**Public**	**Private**	**Public**	**Private**	**Public**
High income (AB)	2,060	4,566	1,332	4,552	-35.34%	-0.31%
Middle income (C)	5,401	4,260	5,474	4,472	1.35%	4.98%
Low income (DE)	311	3,914	991	4,185	218.65%	6.92%

These results indicate that number of households in Central London decreases substantially owing to public transport accessibility improvement. This is an expected result.

4.4.3.4 Private transport travel time

As the consequence of the modal shift to public transport that I have mentioned before, private car use decreases by 32,208. This leads to relief in traffic in some boroughs. However, as I explained before, the number of private transport users increases in some boroughs. Therefore, travel time for private transport increases on some routes.

The most substantial travel time savings are in the journeys starting from Havering -the outermost borough in East London. The route with the highest private car travelling time-saving is Havering – Greenwich with 13.76 minutes (41.48 per cent). Following list shows the private car routes enjoying the highest travel time savings in absolute terms: (i) Havering – Greenwich (13.76 minutes), (ii) Havering – Southwark (13.75 minutes), (iii) Sutton – Hounslow (7.89 minutes) and (iv) Havering – Newham (5.19 minutes). When I aggregate[30] travel time savings on boroughs where the journey starts, the highest travel time saving is achieved for travels originated from Havering. (Figure 4.21) Boroughs with the highest private transport travel time savings

---

[30] In aggregation procedure, private transport travel time for a journey originating from a borough is considered. Number of journeys is not considered in aggregation.

are: (i) Havering (26.76 minutes), (ii) Sutton (9.02 minutes), (iii) Merton (1.34 minutes), (iv) Croydon (0.85 minutes) and (v) Bromley (0.57 minutes).

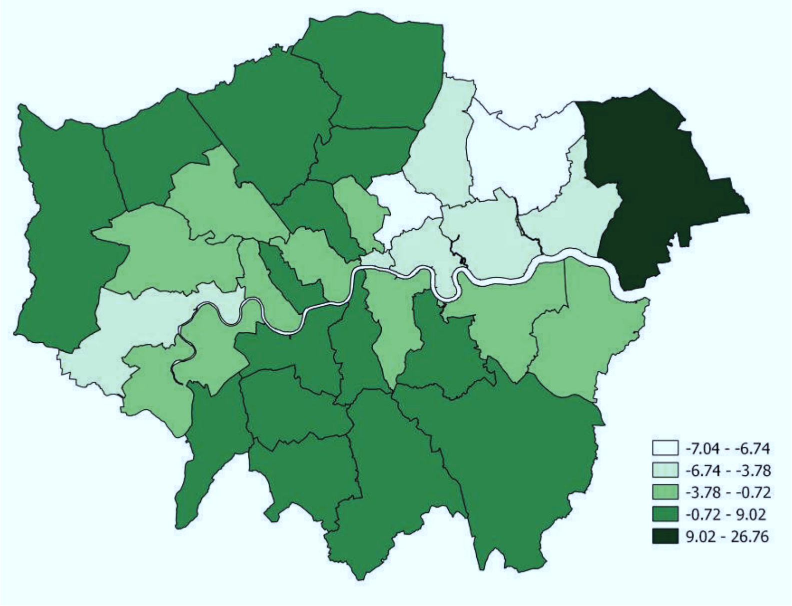


Figure 4.21 Private Transport Travel Time Savings by the Origin of Journey

Figure 4.21 implies that private transport journeys starting from the boroughs on the East-West axis deteriorate in terms of travel time. When investigated in detail, journeys starting from East London to the boroughs Hounslow and Ealing come to the fore in generating such results.[31] This is primarily caused by travel time increases on the roads passing through Central London. Travel times deteriorate the most for the following private transport routes: (i) Redbridge – Ealing (Hounslow): 0.83 minutes (0.84 minutes), (ii) Hackney – Ealing (Hounslow): 0.82 minutes (0.83 minutes), (iii) Havering – Ealing (Hounslow): 0.77 minutes (0.78 minutes), (iv) Barking and Dagenham – Ealing (Hounslow): 0.75 minutes (0.75 minutes), (v) Newham – Ealing (Hounslow): 0.74 minutes (0.75 minutes) and (vi) Tower Hamlets – Ealing (Hounslow): 0.73 minutes (0.74 minutes).

4.5 Discussion

In this chapter, I have used a customised model for London to evaluate the Crossrail 2 project. The primary agents of this model are the commuting households.

---

[31] Hounslow is connected to eastern boroughs through Ealing.

For this reason, only “disutility of travelling” parameter is added to the CES utility function of households, while “utility of neighbourhood” is excluded.

Impacts of the Crossrail 2 project are evaluated in four different impact areas: (i) rental prices, (ii) modal split, (iii) household distribution and (iv) private car travel time.

Model results show that rental price would increase significantly in certain boroughs (Waltham Forest, Merton, Barnet, Enfield and Kingston upon Thames) where the project improves the public transport accessibility. Also, in these boroughs, public transport use increases substantially. Public transport ridership increases by about 24 per cent in Kingston upon Thames, while total ridership increases by 32,280. This overall increase in public transport ridership leads to a remarkable change in the share of public transport from 67 per cent to 71 per cent.

Model results show that number of households in boroughs, in which public transport accessibility is improved due to the Project, increases while central boroughs lose a considerable number of households to these boroughs.

Conditions of private car travels are also improved in some boroughs. Due to the modal shift to public transport, travel times along many routes decrease. The route with the highest private car travelling time-saving is Havering – Greenwich with 13.76 minutes (41.48 per cent). However, relocation of private transport users has negative impacts on private transport travel time in some boroughs. Particularly, travel times for private transport journeys starting from the boroughs on the East-West axis deteriorate. This implies that moving away of households from Central London creates extra traffic (both inflow and transit) in the centre.

The London model is open to enhancement in many ways. First, exclusion of “utility of neighbourhood” may have a substantial impact on the mode accuracy. Also related, is to include the household choice decisions of the non-commuting. This would improve the findings, especially the ones in the housing market. The scale of boroughs is another important point. Analyses show that results for small boroughs are diverging from the others. Using spatial areas where the total population is evenly distributed might be a good option to improve the model accuracy.

Data is at the core of this study. Any improvement in data quality has a positive impact on model accuracy. I had to use aggregate level information to estimate housing unit uses of different groups of households. This is a very critical input data lacking in LTDS. Adding a question on housing unit (number of rooms in this case) use of households to the LTDS is one of the key recommendations of this study.

The last but not the least, including the government in the model as another decision maker will be an important step for improvement, owing to the government's role in Crossrail 2 investment. By this way, a variety of public finance policies can be analysed as different scenarios, particularly in terms of their impacts on households.

CHAPTER 5

CONCLUSION

Policy questions regarding urban economics often deal with the interaction between transport and land use. Accessibility is in the centre of this interaction. Transport policies and projects having impact on the accessibility of places lead to substantial changes in the land use demand and, eventually, in the whole urban economy. Using integrated models that represent such complex interactions between transport, land use and economy has become an attractive field both in transport literature and policy design.

In this Thesis, I have developed a fully-integrated urban CGE model where three blocks of models (economic, household choice and transport) run simultaneously. Integration of the household choice model with the CGE model is achieved by aggregating exact choices of households, where MNL probabilities are used to calculate "market shares" of these choices. On the other hand, I have proposed a new method for embedding the transport (or travel) model into the CGE model. This method transforms "traffic assignment problem" (TAP) into a set of equations while ensuring a unique optimal solution. This set of equations then is utilized as a block representing the choice on travel routes of private transport users in the integrated model.

Chapter 1 provides a brief introduction to arising needs in use of comprehensive modelling tools in urban economics and a literature review of CGE applications in transport studies.

In Chapter 2, model specifications for households and firms, integration procedure of the sub models (economic model, household choice model and travel model) and data requirements have been explained in detail.

In Chapter 3, the proposed model has been utilized to study three distinct scenarios (the capacity increase of private transport, the capacity increase in public transport and cordon pricing) with a synthetic data set for a city with four residential/working districts. Results suggest that heterogeneity among people w.r.t. preferences and valuations (travel time, in particular) is critical in evaluating the effects of transport and land use policies. This means, considering demographic structures of cities and producing accurate parameters for the preferences are crucial for implementing effective policies and good value for money projects.

Chapter 4 provides an application of the proposed model to a real-urban data set. The project chosen to be evaluated in this Chapter is London's Crossrail 2 project that is projected to start in early 2020s and to end in early 2030s. The results of the application show that housing rents would increase significantly in certain boroughs where the project improves the public transport accessibility. For example, price increases in Waltham Forest and Barnet are 8.9 per cent and 8.8 per cent, respectively. The shock (public transport improvement owing to Crossrail 2) also leads to decreases in the housing prices in some boroughs (central boroughs, in particular) as boroughs are competing to attract households from a pool with a fixed number of households. Price decrease in Kensington and Chelsea for instance, is -7.9 per cent.

As expected, implementing the Crossrail 2 project increases the share of public transport use for commuting purposes. The share of public transport increases from 67.3 per cent to 71.0 per cent in London, increasing the number of public transport users by about 32.3 thousand. The highest increases are in the boroughs enjoying the public transport accessibility improvement the most. For example, public transport ridership increases in Kingston upon Thames by 23.6 per cent.

Results show that some boroughs can attract a significant number of households due to the Crossrail 2 project. For example, Barnet attracts around two thousand additional households (6.5per cent increase in the number of households) and Waltham Forest attracts 1.6 thousand (6 per cent increase in the number of households). The highest population losses are in Central London.

This Thesis is the first study that builds up and employs 'full integration' in transport CGE literature. However, the significant contribution of this Thesis also lies in its implementation of a real case using a household survey data. This requires heavy data analysis and critical assumptions at different phases of the consistent database construction. The value of aggregate level of information is not totally ignored, however these should be used only in case of collecting disaggregate level of information is not feasible.

The model proposed is open to improvement in certain directions: First, the public sector should be included in the model to test sound public policies in scenario analyses. Governments' unique role in public investments, social transfers and land use decisions should be modelled to design hybrid policies that are equitable and protecting individuals' rights, particularly excluded groups of people. This is also important to transport projects with a public finance perspective. A second development axis is towards the inclusion of households' discrete choices on working decisions (e.g. working or not working; working place). An accurate model investigating these decisions would represent job market better; therefore, the performance of the integrated model would be improved significantly. The proposed model is comparative static, so it compares two different equilibrium states (Before/After Shock). Transforming this model into a dynamic CGE model would be a promising study.

Because of the special infrastructure and space needs of industries, relocation of a firm is not as easy as one of the households. This makes it hard to model their location choice decisions. For this reason, sticking to the assumption of that location of industries are fixed might still be a good approach in the future studies.

REFERENCES

Anas, A. (1982). *Residential Location Markets and Urban Transportation*, Academic Press, London.

Anas, A. (2013a). A Summary of the Applications to Date of RELU-TRAN, a Microeconomic Urban Computable General Equilibrium Model. *Environment and Planning B: Planning and Design 2013*, 40, 959 – 970.

Anas, A. (2013b). Congestion and Metropolitan Development, Conference Paper, *Twelfth Annual International Conference "Economy and Geography"*, The Leontief Center, St. Petersburg, Russia, February 14-16, 2013.

Anas, A., & Kim, I. (1996). General Equilibrium Models of Polycentric Urban Land Use with Endogenous Congestion and Job Agglomeration. *Journal of Urban Economics*, 40, 232-256.

Anas, A., & Xu, R. (1999). Congestion, Land Use, and Job Dispersion: A General Equilibrium Model. *Journal of Urban Economics*, 45, 451-473.

Anas, A. & Liu, Y. (2007). A Regional Economy, Land Use, and Transportation Model (RELU-TRAN): Formulation, Algorithm Design, and Testing. *Journal of Regional Science*, 47 (3), 415-455.

Anas, A. & Hiramatsu, T. (2012). The Effect of the Price of Gasoline on the Urban Economy: From Route Choice to General Equilibrium. *Transportation Research Part A*, 46, 855-873.

Anas, A. & Hiramatsu, T. (2013). The Economics of Cordon Tolling: General Equilibrium and Welfare Analysis. *Economics of Transportation*, 2, 18–37.

Berg, C. (2007). Household Transport Demand in a CGE-framework. *Environmental & Resource Economics*, 37, 573-597.

Boeters, S., Hordijk, L., Korzhenevych, A., Przeor, M., Swales, K. Vandyck, T., Varga, A., Varga, J. and Wolski, M. (2017). *Review of the RHOMOLO Model.* [Online] Available from: https://ec.europa.eu/jrc/sites/jrcsh/files/review_of_the_rhomolo_model_final.pdf. Last accessed, 10th June 2018.

Bröcker, J. (1998). Operational Spatial Computable General Equilibrium Modelling. *The Annals of Regional Science*, 32, 367–387.

Bröcker, J. (2002). Passenger Flows in CGE Models for Transport Project Evaluation. Conference Paper, *ERSA Congress 2002*, Dortmund, August 2002.

Bröcker, J., Meyer, R., Schneekloth, N., Schürmann, C., Spiekermann, K. & Wegener, M. (2004). Modelling the Socio-economic and Spatial Impacts of EU Transport Policy. IASON (Integrated Appraisal of Spatial economic and Network effects of transport investments and policies) Deliverable 6. Funded by 5th Framework RTD Programme. Kiel/Dortmund: Christian-Albrechts-Universität Kiel/Institut für Raumplanung, Universität Dortmund.

Bröcker, J., Korzhenevych, A. & Schürmann, C. (2010). Assessing spatial equity and efficiency impacts of transport infrastructure projects. *Transportation Research Part B*, 44, 795–811.

Brueckner, J.K. (2011). *Lectures on Urban Economics*. Cambridge, Massachusetts, The MIT Press.

Cardenete, M. A., Guerra, A.I. & Sancho, F. (2012) *Applied General Equilibrium: An Introduction*. Heidelberg, Springer.

Crossrail 2. (2018a) Route map. [ONLINE] Available at: http://crossrail2.co.uk/route/route-map/. [Accessed 28 September 2017].

Crossrail 2. (2018b) Crossrail 2 in numbers. [ONLINE] Available at: http://crossrail2.co.uk/discover/in-numbers/. [Accessed 28 September 2017].

Crossrail 2. (2018c) Regional and national benefits. [ONLINE] Available at: http://crossrail2.co.uk/discover/regional-national-benefits/. [Accessed 26 May 2018].

Dupuit, J. (1844). De la Mesure de l'Utilité des Travaux Publics, *Annales des Ponts et Chaussées*, s. II, 2nd semester, pp. 332-375; English translation by R. H. Barback, On the Measurement of the Utility of Public Works, *International Economic Papers*, 2(1952), 83-110.

Elbers, C., Lanjouw, J. O. & Lanjouw, P. (2003) Micro-Level Estimation of Poverty and Inequality. *Econometrica*, 71 (1), 355-364.

Graham, D.J. (2007). Agglomeration, Productivity and Transport Investment, *Journal of Transport Economics and Policy*, 41(3), 317–343.

Great Britain, Office for National Statistics, *2011 Census*, London.

Great Britain, Valuation Office Agency (VOA), *Private Rental Market Statistics (2014)*, London.

Hensher, D.A., Truong, T.P., Mulley, C. & Ellison, R. (2012). Assessing the wider economy impacts of transport infrastructure investment with an illustrative application to the North-West Rail Link project in Sydney, Australia. *Journal of Transport Geography*, 24, 292-305.

Holden, D. J. (1989). Wardrop's Third Principle: Urban Traffic Congestion and Traffic Policy. *Journal of Transport Economics and Policy*, 23 (3), 239-262.

Horridge, M. (1994). A Computable General Equilibrium Model of Urban Transport Demands. *Journal of Policy Modeling*, 16 (4), 427-457.

Kim, E., Hewings, G. & Hong, C. (2004). An Application of an Integrated Transport Network–Multiregional CGE model: a Framework for the Economic Analysis of Highway Projects. *Economic Systems Research*, 16 (3), 235-258.

Knaap, T. & Oosterhaven, J. (2000). The Welfare Effects of New Infrastructure: An Economic Geography Approach to Evaluating a New Dutch Railway Link, Conference Paper, *North American RSAI Meetings*, Chicago.

Knaap, T. & Oosterhaven, J. (2011). Measuring the Welfare Effects of Infrastructure: A Simple Spatial Equilibrium Evaluation of Dutch Railway Proposals. *Research in Transportation Economics*, 31, 19-28.

LeBlanc, L. J., Morlok, E. K. & Pierskalla, W. P. (1975). An Efficient Approach to Solving the Road Network Equilibrium Traffic Assignment Problem. *Transportation Research*, 9, 5, 309-318.

Lerman, S. R. (1975). *A Disaggregate Behavioural Model of Urban Mobility Decisions*, PhD Thesis, Massachusetts Institute of Technology (MIT).

Magnani, R. & Mercenier, J. (2009). On Linking Microsimulation and Computable General Equilibrium Models Using Exact Aggregation of Heterogeneous Discrete-Choice Making Agents. *Economic Modelling*, 26, 560–570.

McFadden, D. (1977). *Modelling the Choice of Residential Location*, Discussion Paper No. 477, Cowles Foundation for Research in Economics, Yale University.

Mercenier, J., Álvarez-Martinez, M., Brandsma, A., Di Comite, F., Diukanova, O., Kancs, d'A., Lecca, P., López-Cobo, M., Monfort, Ph., Persyn, D., Rillaers, A., Thissen M., and Torfs, W. (2016). *RHOMOLO-v2 Model Description: A spatial computable general equilibrium model for EU regions and sectors*, JRC Technical reports JRC100011, European Commission, DG Joint Research Centre.

Minard, J. (1850). Notions élémentaires d'économie politique appliquée aux travaux publics, *Annales des Ponts et Chaussés: Mémoires et Documents*, 2nd series, 1-125.

Oosterhaven, J. & Knaap, T. (2003). Spatial Economic Impacts of Transport Infrastructure Investments. In: Pearman, A., Mackie, P. & Nellthorp, J. (Eds.), *Transport Projects, Programmes and Policies: Evaluation Needs and Capabilities*, Ashgate, Aldershot, 2003.

Patriksson, M. (1994). *The Traffic Assignment Problem-models and Methods*, Utrecht, VSP.

Peichl, A. (2008). *The Benefits of Linking CGE and Microsimulation Models: Evidence from a Flat Tax Analysis*, IZA DP No.3715.

Pigou, A.C. (1920). *The Economics of Welfare*. 1st ed. London: MACMILLAN AND CO., LIMITED.

Robiliard, A-S., Bourguignon, F. & Robinson, S. (2001). *Crisis and Income Distribution: A Micro-Macro Model for Indonesia*, Technical report, International Food Policy Research Institute, Washington, D.C.

Robson, E. & Dixit, V. (2015). A Review of Computable General Equilibrium Modelling for Transport Appraisal, Conference Paper, *Conference of Australian Institutes of Transport Research 2015.* University of Melbourne, 12–13 February 2015.

Rutherford, T. F. & Van Nieuwkoop, R. (2011). An Integrated Transport Network - Computable General Equilibrium Models for Zurich. *Swiss Transport Research Conference.* Zurich: Center for Energy Policy and Economic, Department of Management, Technology and Economics, ETH.

Samuelson, P. A. (1954). The Transfer Problem and Transport Costs, II: Analysis of Effects of Trade Impediments. *The Economic Journal*, Vol. 64, No. 254, 264–289.

Santos, G. & Newbery, D. (2001). *Urban congestion charging: theory, practice and environmental consequences*. CESifo Working Paper No. 568. Munich, Germany.

Sato, T. & Hino, S. (2005). A Spatial CGE Analysis of Road Pricing in the Tokyo Metropolitan Area. *Journal of the Eastern Asia Society for Transportation Studies*, 6, 608 – 623.

Tang, C.K. (2016). Traffic Externalities and Housing Prices: Evidence from the London Congestion Charge. SERC Discussion Paper No. 205. London, United Kingdom.

TOMTOM, *Traffic Index: Measuring Congestion Worldwide.* [Online] Available from: https://www.tomtom.com/en_gb/trafficindex/#/. Last accessed, 10th June 2018.

Train, K. E. (2002). *Discrete Choice Methods with Simulation,* Unpublished Version Before First Edition.

Train, K. E. (2009). *Discrete Choice Methods with Simulation,* Second Edition. Cambridge Books, Cambridge University Press. 3.

Transport for London (TfL), *London Travel Demand Survey (LTDS) 2014*, London.

Transport for London (TfL) (2015) Crossrail 2 factsheets and leaflets. [ONLINE] Available at: https://consultations.tfl.gov.uk/crossrail2/october2015/#Crossrail 2 Factsheets. [Accessed 28 September 2017].

Transport for London (TfL) (2018) Fares & payments. [ONLINE] Available at: https://tfl.gov.uk/fares-and-payments/. [Accessed 28 September 2017].

Treiber, M., Kesting, A. & Thieman, C. (2008) How Much Does Traffic Congestion Increase Fuel Consumption and Emissions? Applying Fuel Consumption Model to NGSIM Trajectory Data. *Transportation Research Board 87th Annual Meeting*, Washington DC, United States, January 2008.

Truong, T. P., & Hensher, D. A. (2012). Linking Discrete Choice to Continuous Demand within the Framework of a Computable General Equilibrium Model. *Transportation Research Part B*, 46, 1177-1201.

Verikios, G. & Zhang, X-G. (2015). Reform of Australian Urban Transport: A CGE-Microsimulation Analysis of the Effects on Income Distribution. *Economic Modelling*, 44, 7–17.

Wardrop, J. G. (1952). Some Theoretical Aspects of Road Traffic Research. Road Paper No.36. *Proceedings of the Institution of Civil Engineers*, 325-362.

Wegener, M. & Bökemann, D. (1998). *The SASI Model: Model Structure*. SASI Deliverable D8. Berichte aus dem Institut für Raumplanung 40. Dortmund: Institut für Raumplanung, Universität Dortmund.

Zhu, J., Jin, Y. & Echenique, M. (2012). Application of a New Spatial Computable General Equilibrium Model for Assessing Strategic Transport and Land Use Development Options in London and Surrounding Regions, Conference Paper, *ERSA Congress 2012*, Bratislava, August 2012.

APPENDICES

APPENDIX A: MATHEMATICAL STATEMENT FOR THE MODEL

SETS

$i, w \in R$	Residential and working locations
$m \in T$	Commute mode (0: no commute, 1: car, 2: public transport, 3: other modes)
$g \in G$	Skill used in production (0: non-working, 1: low skill, 2: high skill)
$l \in C$	Commodities (consumption goods and services)

PARAMETERS

α_{iwmg}^{l}	Share parameter for a commodity
α_{iwmg}^{h}	Share parameter for housing
Ψ_i	Neighbourhood utility
γ_{iwmg}	Negative utility of commuting
e_{iwmg}^{K}	Household capital possession
$e_{iwmg}^{H}\left(i^{'}\right)$	Household housing possession at a specific location
$N\left(w, g\right)$	Number of households with specific working locations and skill levels
VA_l	Value-added of industry l
v_l	Quantity of value-added needed for one-unit production of output y_l
a_{kl}	Input-output coefficient
ϕ_l	Total factor productivity
β_l	CES production function factor coefficient
β_l^L	Share of skilled labour for industry l

$\Delta^{iw}_{a,path}$	Link-path incidence parameter
A_a	Time required to traverse link under no traffic congestion
B_a	Traffic congestion coefficient for link
Q_a	Link capacity
C^f	Fuel consumption under no congestion
C^c	Fuel consumption under a reference congestion level
τ^f_{iwm}	Travel time under no congestion
t^f_{100}	Reference travel time under no congestion (h/100 km)
t^c_{100}	Reference travel time under a reference congestion level (h/100 km)
D_{iw}	Distance between *i* and *w*
p^f	Fuel cost

VARIABLES

$c_{iwmg,l}$	Household consumption on a commodity
d_{iwmg}	Household consumption on housing (floor-space, rooms) at location *i*
C_l	Total demand for consumption goods
D_i	Total demand for housing
τ_{iwm}	Commute time
κ_{iwm}	Commute cost
M_{iwmg}	Total household income (earned income + unearned income)
r_i	Rental rate per housing unit (floor-space, rooms)
p_l	Commodity price
w_g	Labour price (=earned income)
δ	Capital price
$P_{w,g}\left(i,m\right)$	Household location and transport mode choice probability
$N_{i,m}\left(w,g\right)$	Number of households selecting specific housing location and transport mode
y_l	Output of industry *l*

x_a	Traffic flow on link *a*
$t_a\left(x\right)$	Travel time on link *a*
q_{iw}	Travel demand from *i* to *w*
f_{path}^{iw}	Traffic flow on a path from *i* to *w*
$\pi\left(i,w\right)$	Number of paths used for journeys from *i* to *w*

APPENDIX B: OPTIMAL USER EQUILIBRIUM SOLUTION

Wardrop (1952) introduced road traffic equilibrium principles, which constitute foundations of many travel models. Wardrop's First Principle proposes that traffic reaches an equilibrium state where no driver can reduce travel time (be better off) by choosing another route. This principle is often attributed to "user equilibrium (UE)" in the literature: "The journey times on all the routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused route."

User equilibrium model (or traffic assignment problem - TAP) is formulated as in the following link-route representation:

(1) Objective function minimising total travel times on links using a convex and non-decreasing travel time function:

$$\min z(x) = \sum_a \int_0^{x_a} t_a(x)\, dx \tag{B.1}$$

s.t.

(2) Balancing travel demand:

$$\sum_p f_p^{od} = q_{od} \qquad \left(f_p^{od} \geq 0\right) \tag{B.2}$$

(3) Traffic flow on a link:

$$x_a = \sum_o \sum_d \sum_p f_p^{od} \cdot \Delta_{a,p}^{od} \tag{B.3}$$

where,

x_a = traffic flow on link a
$t_a(x)$ = travel time on link a (convex non-decreasing function)
q_{od} = travel demand from o to d
f_p^{od} = traffic flow on path p from o to d
$\Delta_{a,p}^{od}$ = binary variable (1 if link a belongs to path p from o to d, 0 otherwise)

Assuming travel time function is strictly increasing with a fixed demand for each origin-destination pair, we know that there exists an optimal user equilibrium flow and it is unique. (See Patriksson, 1994)

Solving traffic assignment problem does not only give us travel times between nodes but also which links are used for these journeys. Therefore, we obtain values for binary variable $\delta_{a,p}^{od}$ by solving the problem defined above. That means that if assume that link-path incidence parameter values $\left(\delta_{a,p}^{od}\right)$ are given, travel times for each journey can be solved by using the following equation steps:

(1) Balancing travel demand (A.2.2):

$$\sum_p f_p^{od} = q_{od} \quad \left(f_p^{od} \geq 0\right)$$

(2) Traffic flow on a link (A.2.3):

$$x_a = \sum_o \sum_d \sum_p f_p^{od} \cdot \Delta_{a,p}^{od}$$

(3) Travel time definition:

$$t_a = \mathrm{A}_a + \mathrm{B}_a \left[\frac{x_a}{Q_a}\right]^4 \tag{B.4}$$

(4) Travel time of a path from *o* to *d*:

$$t_p^{od} = \sum_a t_a \cdot \Delta_{a,p}^{od} \tag{B.5}$$

(5) Wardrop's First Principle:

$$t_p^{od} = t_{p'}^{od} \quad \forall p' \left(f_{p'}^{od} > 0\right) \tag{B.6}$$

If we show that the above equation set provides a unique solution that is the same with the optimal solution of the user equilibrium problem, we can embed this equation set into the CGE framework as travel modelling block.

If people travelling from node A to node E use two different paths: (i) $|AE|$ and (ii) $|AD|+|DE|$. It is to be noted that link $|AE|$ is used only for journeys between node A and node E while link $|AD|$ and link $|DE|$ are used for other journeys.

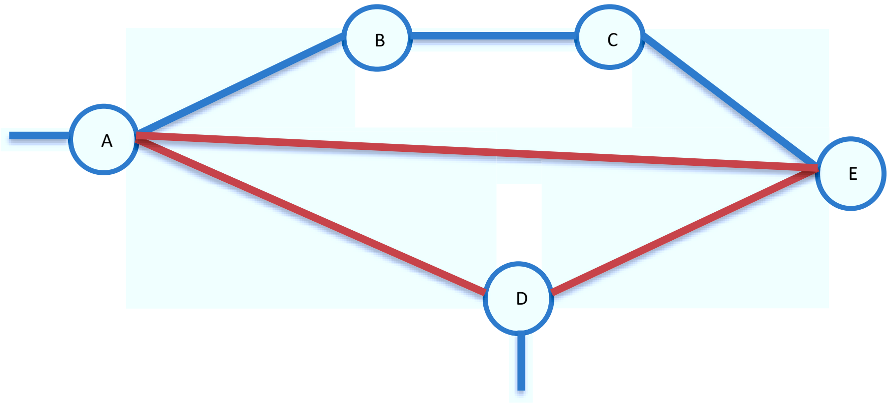


Figure B.1 Small Road Network

In accordance with Wardrop's First Principle, the following equation should be held:

$$t_{AD}\left(a+x\right)+t_{DE}\left(b+x\right)=t_{AE}\left(q_{AE}-x\right) \tag{B.7}$$

where x is the number of people using links $|AD|$ and $|DE|$ in order to go from node A to node E. Rewriting above equation in functional form,

$$\underbrace{t_{AD}\left(a+x\right)+t_{DE}\left(b+x\right)-t_{AE}\left(q_{AE}-x\right)=0}_{g(x)} \tag{B.8}$$

Since travel time function is a convex and strictly increasing function,

$$\frac{\partial g\left(x\right)}{\partial x}=t_{AD}^{'}\left(a+x\right)+t_{DE}^{'}\left(b+x\right)+t_{AE}^{'}\left(q_{AE}-x\right)>0 \tag{B.9}$$

This shows that $g\left(x\right)$ is also strictly increasing. And for $x=0$,

$$g\left(0\right)=t_{AD}\left(a\right)+t_{DE}\left(b\right)-t_{AE}\left(q_{AE}\right)<0 \tag{B.10}$$

Therefore, for a unique value of $x>0$, $g\left(x\right)=0$ will be held. This concludes our proof.

APPENDIX C: VERIFYING ALGORITHM

To find equilibrium solution, it is needed to verify that the matrix for link-path incidence parameters (Δ) is the matrix at the equilibrium condition. Following algorithm is used to do this verification:

```
Step 0: Form the transport network after the shock (project or policy change)
Step 1: Run Traffic Assignment Problem (UE)
Step 2: Form the matrix for link-path incidence parameters ($\Delta_0$)
Step 3: Run full model using $\Delta_0$
Step 4: Form the OD matrix
Step 5: Run Traffic Assignment Problem (UE) using OD matrix
Step 6: Form the matrix for link-path incidence parameters ($\Delta_1$)
Step 7: If $\Delta_0=\Delta_1$ STOP, Else SET $\Delta_0=\Delta_1$ AND GOTO Step 3
```

APPENDIX D: ROY’S IDENTITY

$$\frac{\partial V}{\partial p_l} = -\left(M_{iwmg} - \kappa_{iwm}\right)\left(\frac{\alpha_{iwmg}^{l}}{p_l}\right)^{\sigma} \frac{\left[\left(\alpha_{iwmg}^{h}\right)^{\sigma} r_i^{1-\sigma} + \sum_{k=1}^{n}\left(\alpha_{iwmg}^{k}\right)^{\sigma} p_k^{1-\sigma}\right]^{1/(\sigma-1)}}{\left(\alpha_{iwmg}^{h}\right)^{\sigma} r_i^{1-\sigma} + \sum_{l=1}^{n}\left(\alpha_{iwmg}^{l}\right)^{\sigma} p_l^{1-\sigma}}$$

$$= -c_{iwmg,l}\left[\left(\alpha_{iwmg}^{h}\right)^{\sigma} r_i^{1-\sigma} + \sum_{k=1}^{n}\left(\alpha_{iwmg}^{k}\right)^{\sigma} p_k^{1-\sigma}\right]^{1/(\sigma-1)} \qquad \text{(D.1)}$$

$$= -c_{iwmg,l}\lambda; \quad \therefore \lambda = \left[\left(\alpha_{iwmg}^{h}\right)^{\sigma} r_i^{1-\sigma} + \sum_{k=1}^{n}\left(\alpha_{iwmg}^{k}\right)^{\sigma} p_k^{1-\sigma}\right]^{1/(\sigma-1)}$$

$$\frac{\partial L}{\partial p_1} = -c_1\lambda \qquad \text{(D.2)}$$

From $\rho = \frac{\sigma - 1}{\sigma}$:

$$\lambda p_l = \alpha_{iwmg}^{l}\left[\sum_{l=1}^{n}\alpha_{iwmg}^{l} c_{iwmg,l}^{\frac{\sigma-1}{\sigma}} + \alpha_{iwmg}^{h} d_{iwmg}^{\frac{\sigma-1}{\sigma}}\right]^{1/(\sigma-1)} c_{iwmg,l}^{-1/\sigma} \qquad \text{(D.3)}$$

$$\lambda = \left[\left(\alpha_{iwmg}^{h}\right)^{\sigma} r_i^{1-\sigma} + \sum_{k=1}^{n}\left(\alpha_{iwmg}^{k}\right)^{\sigma} p_k^{1-\sigma}\right]^{1/(\sigma-1)} \qquad \text{(D.4)}$$

QED. This proves the Roy’s Identity.

APPENDIX E: MULTINOMIAL LOGIT (MNL) PROBABILITY FOR HOUSEHOLD CHOICE

In the context of urban studies, where people choose to live and how they decide on this choice are important questions attracting widespread attention from different disciplines. This makes the prediction of households' future residential locations a critical part of urban economic models. Although people's choices on their residential locations are based on different economic theories, after the seminal academic studies of Lerman (1975) and McFadden (1977), disaggregate behavioural models based on the theory of consumer choice in microeconomics have stepped forward. This has led to a paradigm shift in residential location choice models, favouring discrete choice models where the conceptual basis relies on the observation that individuals make their choices among the given alternatives and the outcome variables are discrete (Train, 2009:3).

Discrete choice models assume that decision makers (individuals, households, private companies, government etc.) decide on their choices maximising their utilities. As a point that distinguishes discrete choice models from the alternatives, utilities of decision makers in these models are represented employing random (unobserved) components besides the deterministic (observed) ones. This allows discrete choice models to represent heterogeneity among different agents. Hence, any decision maker *n* chooses among *J* alternatives using the following utility function:

$$U_{ni} = V_{ni} + \varepsilon_{ni} \qquad \left(i = 0, 1, 2..., J\right) \tag{E.1}$$

where V_{ni} denotes the "representative utility" observed by a researcher and ε_{ni} is the random component of the utility that cannot be included in V_{ni} (Train, 2002:19). Hence, the condition $U_{ni} > U_{nj} \left(i \neq j\right)$ would lead decision maker *n* to choose alternative *i* among the other alternatives. Due to the random component of the utility, the probability of choosing alternative *i* can be written as follows:

$$\begin{aligned} P_{ni} &= prob\left[U_{ni} > U_{nj}, \forall j \neq i\right] \\ &= prob\left[V_{ni} + \varepsilon_{ni} > V_{nj} + \varepsilon_{nj}, \forall j \neq i\right] \\ &= prob\left[\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj}, \forall j \neq i\right] \end{aligned} \tag{E.2}$$

It should be noted that the above definition of choice probability denotes the cumulative distribution of the random variable $\varepsilon_{nj} - \varepsilon_{ni}$. Because of the assumption that decision makers make their decisions on different alternatives considering their relative attractiveness, choice probability depending on the difference in utility makes sense (Train, 2002:25).

In general, choosing discrete choice models, specifying observed part of utility –representative utility- linear in parameters is a common approach as in the following transport mode choice example from Train (2002). In this example, observed parts of utilities for each mode (car and bus) are specified according to mode specific and socio-demographic attributes:

$$\begin{aligned} V_c &= \alpha T_c + \beta M_c + \theta_c^0 Y + k_c^0 \\ V_b &= \alpha T_b + \beta M_b + \theta_b^0 Y + k_b^0 \end{aligned} \tag{E.3}$$

where *T* and *M* are time and monetary costs of using the relevant mode, respectively, Y denotes the income of the decision maker, θ_c^0 and θ_b^0 are the relevant parameters capturing the effect of any change in income level on utility levels of relevant transport modes, and k_c^0 and k_b^0 denote "alternative specific constants" for each transport mode. As mentioned above, considering difference in utilities makes sense for a decision maker (or a researcher) in choosing among alternatives. Hence, we can define new parameters associated to the utility of taking the bus compared to taking the car: $\theta_b = \theta_b^0 - \theta_c^0$ and $k_b = k_b^0 - k_c^0$. This leads to the following utilities for each transport mode:

$$\begin{aligned} V_c &= \alpha T_c + \beta M_c \\ V_b &= \alpha T_b + \beta M_b + \theta_b Y + k_b \end{aligned} \tag{E.4}$$

Considering differences in random variables for each alternative, we define a new random variable $\varepsilon_n = \varepsilon_{nj} - \varepsilon_{ni}$ for a decision maker *n*. We assume that each random component of the utility has a Gumbel distribution, which is a special case of generalized extreme value (GEV) distribution.

$$\varepsilon_{ni} \sim \text{Gumbel}\left(\eta_i, \mu\right) \tag{E.5}$$

The cumulative distribution function would be:

$$F\left(\varepsilon_{ni}\right) = \exp\left(-e^{-\mu\left(\varepsilon_{ni}-\eta_i\right)}\right) \tag{E.6}$$

Since the difference of two Gumbel-distributed random variables $\left(\varepsilon_n = \varepsilon_{nj} - \varepsilon_{ni}\right)$ is logistically distributed, we can define the cumulative distribution function of the random variable ε_n as in the following equation:

$$F\left(\varepsilon_n\right) = \frac{1}{1+\exp\left(\mu\left[\eta_j - \eta_i - \varepsilon_n\right]\right)} \tag{E.7}$$

Turning to the choice probability of an alternative, we can write the probability of choosing alternative 1 among *J* alternatives as follows:

$$P_n\left(1\right) = prob\left[\underbrace{V_{n1} + \varepsilon_{n1}}_{U_1} \geq \underbrace{\max_{j=2,\dots,J}\left(V_{nj} + \varepsilon_{nj}\right)}_{U^*}\right] \tag{E.8}$$

where $U^* = V^* + \varepsilon^*$ and all disturbance terms are Gumbel distributed with $\eta = 0$. Therefore, in accordance with Gumbel distribution properties, distributions for each utility function become:

$$\begin{aligned} U_1 &\sim \text{Gumbel}\left(V_{n1}, \mu\right) \\ U^* &\sim \text{Gumbel}\left(\frac{1}{\mu}\ln\sum_{j=2}^{J} e^{\mu V_{nj}}, \mu\right) \end{aligned} \tag{E.9}$$

Hence, the probability of choosing alternative 1 among *J* alternatives becomes a binary choice model:

$$P_n\left(1\right) = prob\left[U_1 - U^* \geq 0\right] \tag{E.10}$$

And by the definition of the logistic distribution:

$$P_n(1) = \frac{1}{1+e^{\mu\left(V^* - V_{n1}\right)}} = \frac{e^{\mu V_{n1}}}{e^{\mu V_{n1}} + e^{\mu V^*}} \tag{E.11}$$

From the definition $V^* = \frac{1}{\mu}\ln\sum_{j=2}^{J} e^{\mu V_{nj}}$, we can conclude that:

$$P_n(1) = \frac{e^{\mu V_{n1}}}{e^{\mu V_{n1}} + \sum_{j=2}^{J} e^{\mu V_{nj}}} = \frac{e^{\mu V_{n1}}}{\sum_{j=1}^{J} e^{\mu V_{nj}}} \tag{E.12}$$

Scale parameter μ scales the coefficients reflecting unobserved utility variance. In fact, this is not estimated separately but with the other coefficients. Therefore, the probability of choosing alternative 1 among other alternatives can be written in this well-known form:

$$P_n(1) = \frac{e^{V_{n1}}}{\sum_{j=1}^{J} e^{V_{nj}}} \tag{E.13}$$

APPENDIX F: HOUSEHOLD LOCATION AND TRANSPORT MODE CHOICE PROBABILITY

The probability for residential location and transport mode choices of a household with attributes of working location and skill level pairs (w,g) can be written as in the following form:

$$P_{w,g}(i,m) = P_{w,g}(i) \cdot P_{w,g}(m \mid i) \tag{F.1}$$

The probability of choosing location *i* as the residential location is:

$$P_{w,g}(i) = \frac{\sum_{m'} e^{V_{iwm'g}}}{\sum_{j}\sum_{m'} e^{V_{jwm'g}}} \tag{F.2}$$

The probability of choosing mode *m* as the preferred transport mode for a household residing at location *i* is:

$$P_{w,g}(m \mid i) = \frac{e^{V_{iwmg}}}{\sum_{m'} e^{V_{iwm'g}}} \tag{F.3}$$

This leads to:

$$P_{w,g}(i,m) = \frac{\sum_{m'} e^{V_{iwm'g}}}{\sum_{j}\sum_{m'} e^{V_{jwm'g}}} \cdot \frac{e^{V_{iwmg}}}{\sum_{m'} e^{V_{iwm'g}}} = \frac{e^{V_{iwmg}}}{\sum_{j}\sum_{m'} e^{V_{jwm'g}}} \tag{F.4}$$

Finally, we can write probability of choosing residential location *i* and transport mode *m* as follows:

$$P_{w,g}(i,m) = \frac{\exp\left(\left[\sum_{l=1}^{n} \alpha_{iwmg}^{l} c_{iwmg,l}^{\rho} + \alpha_{iwmg}^{h} d_{iwmg}^{\rho}\right]^{1/\rho} + \Psi_{i} - \gamma_{iwmg}\tau_{iwm}\right)}{\sum_{j}\sum_{m'} \exp\left(\left[\sum_{l=1}^{n} \alpha_{jwm'g}^{l} c_{jwm'g,l}^{\rho} + \alpha_{jwm'g}^{h} d_{jwm'g}^{\rho}\right]^{1/\rho} + \Psi_{j} - \gamma_{jwm'g}\tau_{jwm'}\right)} \tag{F.5}$$

APPENDIX G: LONDON TRAVEL DEMAND SURVEY (LTDS) DATA

LTDS 2014 microdata is used in this study. Two main tables from this database is used:

1) Household
2) Trip

Household table provides more than 50 household attributes including home address, household income, number of vehicles, etc. Trip table provides specific information about trips like trip origin and destination, purpose of trips, distance of trips and duration of trips. Trip table also has a specific Household ID attribute that enables us to merge two tables. Using these two LTDS tables and provided weights for household categories, I take the following attributes to create a household table we need in our analyses:

- A unique household number for each household
- Origin postcode representing residential location (for example, NW1)
- Destination postcode representing working location (for example, NW1)
- Household income level
- Preferred commuting mode
- Commute time (min)
- Commute distance (km)
- Weight

Taking the table with these attributes as the primary data source and using secondary data sources explained in Table 3.1, I create another household table, which is the main data of the model. This table has the following attributes:

Household Table:

- Location Information:
  - Residential (at borough level)
  - Working (at borough level)
- Household group (AB, C, DE)

- Commuting mode (private transport (car), public transport including NMT)
- Count (household number)
- Expenditure:
  - Room number (number of spaces)
  - Composite good (quantity)

APPENDIX H: GREATER LONDON AREA POPULATION STATISTICS

Code	Borough	Inner/ Outer	Population Estimate (2014)	Census population (2011)
E09000001	City of London	Inner	6,872	7,400
E09000002	Barking and Dagenham	Outer	198,683	185,900
E09000003	Barnet	Outer	375,030	356,400
E09000004	Bexley	Outer	240,093	232,000
E09000005	Brent	Outer	321,601	311,200
E09000006	Bromley	Outer	321,834	309,400
E09000007	Camden	Inner	234,845	220,300
E09000008	Croydon	Outer	376,040	363,400
E09000009	Ealing	Outer	342,469	338,400
E09000010	Enfield	Outer	324,650	312,500
E09000011	Greenwich	Outer	268,678	254,600
E09000012	Hackney	Inner	263,546	246,300
E09000013	Hammersmith and Fulham	Inner	178,710	182,500
E09000014	Haringey	Inner	268,439	254,900
E09000015	Harrow	Outer	246,575	239,100
E09000016	Havering	Outer	246,328	237,200
E09000017	Hillingdon	Outer	293,325	273,900
E09000018	Hounslow	Outer	265,975	254,000
E09000019	Islington	Inner	221,383	206,100
E09000020	Kensington and Chelsea	Inner	156,591	158,700
E09000021	Kingston upon Thames	Outer	169,991	160,100
E09000022	Lambeth	Inner	318,543	303,100
E09000023	Lewisham	Inner	292,520	275,900
E09000024	Merton	Outer	204,198	199,700
E09000025	Newham	Inner	325,774	308,000
E09000026	Redbridge	Outer	293,181	279,000
E09000027	Richmond upon Thames	Outer	193,585	187,000
E09000028	Southwark	Inner	303,182	288,300
E09000029	Sutton	Outer	198,526	190,100
E09000030	Tower Hamlets	Inner	284,688	254,100
E09000031	Waltham Forest	Outer	268,675	258,200
E09000032	Wandsworth	Inner	312,735	307,000
E09000033	Westminster	Inner	233,292	219,400
E13000001	Inner London		3,401,119	3,231,900
E13000002	Outer London		5,149,436	4,942,100
E12000007	London		8,550,555	8,173,900

APPENDIX I: PUBLIC TRANSPORT TRAVEL TIME SAVINGS AFTER CROSSRAIL 2

Crossrail 2 factsheets provide some estimated figures in travel time savings for some of the routes connecting some areas including Angel, Clapham Junction, Dalston, Kings Road Chelsea, Raynes Park, Tottenham Court Road and Wimbledon. First, these figures are used to estimate travel times savings on the main route of the Crossrail 2. Second, for each OD pair, used segments of the Crossrail 2 for public transport journeys are identified. Third, due to increase in the number of trains passing through the city centre, a travel time saving of 2-minutes is added to central boroughs. Finally, resulting travel time saving for each pair is calculated as displayed in below tables.

		TO																
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
FROM	**1**	0	0	0	2	2	2	2	2	2	0	2	4	2	12	2	2	2
	2	0	0	2	0	4	10	17	17	10	5	4	10	17	5	0	0	0
	3	0	2	0	2	0	2	2	2	2	12	2	4	2	12	2	2	2
	4	2	0	2	0	2	0	2	2	0	12	2	2	2	12	0	2	0
	5	2	4	0	2	0	2	2	0	2	12	0	4	2	12	2	2	2
	6	2	10	2	0	2	0	2	2	2	10	2	2	2	10	2	2	2
	7	2	17	2	2	2	2	0	2	2	12	2	4	2	12	2	2	2
	8	2	17	2	2	0	2	2	0	2	12	2	4	2	12	2	2	2
	9	2	10	2	0	2	2	2	2	0	12	2	4	2	12	0	0	0
	10	0	5	12	12	12	10	12	12	12	0	4	5	12	2	14	7	14
	11	2	4	2	2	0	2	2	2	2	4	0	2	2	14	2	0	0
	12	4	10	4	2	4	2	4	4	4	5	2	0	4	5	4	0	4
	13	2	17	2	2	2	2	2	2	2	12	2	4	0	12	2	2	2
	14	12	5	12	12	12	10	12	12	12	2	14	5	12	0	14	0	14
	15	2	0	2	0	2	2	2	2	0	14	2	4	2	14	0	2	0
	16	2	0	2	2	2	2	2	2	0	7	0	0	2	0	2	0	2
	17	2	0	2	0	2	2	2	2	0	14	0	4	2	14	0	2	0

TO

FROM

	18	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
1	2	4	2	17	2	2	12	0	0	2	2	2	2	0	7	2
2	17	10	17	32	17	17	27	12	0	19	17	17	19	0	22	17
3	2	4	2	17	2	2	12	2	2	2	2	2	2	12	7	2
4	0	2	2	17	2	2	12	2	2	0	2	2	2	7	7	2
5	2	4	2	17	0	0	12	2	2	2	2	0	2	12	7	2
6	2	2	2	17	2	2	12	2	2	2	2	2	2	10	7	2
7	2	4	2	17	2	2	12	2	2	2	2	12	2	12	7	2
8	2	4	2	5	0	0	0	2	2	0	2	0	2	12	0	2
9	0	4	2	17	2	2	12	0	0	0	2	2	0	12	7	2
10	14	5	12	27	12	14	22	7	7	14	14	14	14	7	17	12
11	2	2	2	17	2	0	12	0	0	2	2	2	0	0	7	2
12	4	2	4	19	4	4	14	0	0	4	4	4	0	5	9	4
13	2	4	2	17	2	2	12	2	2	2	2	12	2	12	7	2
14	14	5	12	27	12	14	22	0	0	14	12	12	14	0	17	12
15	0	4	2	17	2	2	12	2	2	0	2	2	2	12	7	2
16	2	0	2	17	2	0	12	0	0	0	2	2	0	0	7	2
17	0	4	2	0	0	2	0	2	2	0	2	0	0	12	0	2

TO

FROM

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
18	2	17	2	0	2	2	2	2	0	14	2	4	2	14	0	2	0
19	4	10	4	2	4	2	4	4	4	5	2	2	4	5	4	0	4
20	2	17	2	2	2	2	2	2	2	12	2	4	2	12	2	2	2
21	17	32	17	17	17	17	17	5	17	27	17	19	17	27	17	17	0
22	2	17	2	2	0	2	2	0	2	12	2	4	2	12	2	2	0
23	2	17	2	2	0	2	2	0	2	14	0	4	2	14	2	0	2
24	12	27	12	12	12	12	12	0	12	22	12	14	12	22	12	12	0
25	0	12	2	2	2	2	2	2	0	7	0	0	2	0	2	0	2
26	0	0	2	2	2	2	2	2	0	7	0	0	2	0	2	0	2
27	2	19	2	0	2	2	2	0	0	14	2	4	2	14	0	0	0
28	2	17	2	2	2	2	2	2	2	14	2	4	2	12	2	2	2
29	2	17	2	2	0	2	12	0	2	14	2	4	12	12	2	2	0
30	2	19	2	2	2	2	2	2	0	14	0	0	2	14	2	0	0
31	0	0	12	7	12	10	12	12	12	7	0	5	12	0	12	0	12
32	7	22	7	7	7	7	7	0	7	17	7	9	7	17	7	7	0
33	2	17	2	2	2	2	2	2	2	12	2	4	2	12	2	2	2

TO

FROM

	18	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
18	0	4	2	0	0	2	0	2	2	0	2	0	0	12	0	2
19	4	0	4	19	4	4	14	0	0	4	4	4	0	5	9	4
20	2	4	0	17	2	2	12	2	2	2	2	12	2	12	7	2
21	0	19	17	0	5	10	5	17	17	0	17	0	17	27	10	17
22	0	4	2	5	0	0	5	2	2	0	2	0	2	12	0	2
23	2	4	2	10	0	0	5	0	0	2	2	0	0	12	0	2
24	0	14	12	5	5	5	0	12	12	0	12	0	12	22	5	12
25	2	0	2	17	2	0	12	0	0	0	2	2	0	0	7	2
26	2	0	2	17	2	0	12	0	0	0	2	2	0	0	7	2
27	0	4	2	0	0	2	0	0	0	0	2	2	0	12	0	2
28	2	4	2	17	2	2	12	2	2	2	0	12	2	12	7	2
29	0	4	12	0	0	0	0	2	2	2	12	0	2	12	5	12
30	0	0	2	17	2	0	12	0	0	0	2	2	0	0	7	2
31	12	5	12	27	12	12	22	0	0	12	12	12	0	0	17	12
32	0	9	7	10	0	0	5	7	7	0	7	5	7	17	0	7
33	2	4	2	17	2	2	12	2	2	2	2	12	2	12	7	0

APPENDIX J: ANNUAL RENTAL RATES (POUNDS/ROOM) (2014)

Barking and Dagenham	2,764	Hounslow	4,258
Barnet	4,383	Islington	5,890
Bexley	2,781	Kensington and Chelsea	9,997
Brent	4,474	Kingston upon Thames	4,056
Bromley	3,477	Lambeth	4,790
Camden	6,535	Lewisham	3,730
City of London	7,620	Merton	4,339
Croydon	3,198	Newham	3,620
Ealing	4,429	Redbridge	3,162
Enfield	3,524	Richmond upon Thames	5,385
Greenwich	3,881	Southwark	4,854
Hackney	5,148	Sutton	3,301
Hammersmith and Fulham	5,850	Tower Hamlets	5,003
Haringey	4,451	Waltham Forest	3,399
Harrow	3,605	Wandsworth	5,018
Havering	2,772	Westminster	8,910
Hillingdon	3,336		

Source: Valuation Office Agency (VOA), Private Rental Market Statistics (2014)

APPENDIX K: CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name: Yılmaz, Özhan
Nationality: Turkish (TR)
Date and Place of Birth: 27 September 1981, Osmancık
Marital Status: Married
Phone: +90 505 368 39 78
email: ozhan.yilmaz@yahoo.com.tr

EDUCATION

Degree	**Institution**	**Year of Graduation**
MS	Imperial College London & University College London Transport Studies	2014
MS	METU Industrial Engineering	2009
BS	Bilkent University Industrial Engineering	2003
High School	Ankara Science High School, Ankara	1999

WORK EXPERIENCE

Year	**Place**	**Enrollment**
2017- Present	European Investment Bank	Engineer
2006-2017	Ministry of Development	Planning Specialist
2005-2006	HSBC	IT Auditor
2004-2005	Halkbank	Auditor

FOREIGN LANGUAGES

Advanced English, Intermediate French, Basic German

PUBLICATIONS

1. Yilmaz O, Savasaneril S (2012) Collaboration among small shippers in a transportation market. European Journal of Operational Research 218(2):408–415

APPENDIX L: TURKISH SUMMARY / TÜRKÇE ÖZET

GİRİŞ

Ulaşım, birkaç istisna dışında (örneğin, kruvaziyer yolculuk), her ne kadar nihai bir ürün olarak değerlendirilmese de ekonomik aktivitelerin hayata geçirilmesinde önemli bir yere sahiptir. Ulaşım ağının (altyapısının) yetersiz olduğu durumlarda ekonominin etkin bir şekilde çalışması mümkün olmamaktadır. Ulaşım altyapısı bir yandan insanların ve endüstrilerin ihtiyaç duyduğu mal ve hizmetlere erişim kanallarını sağlarken bir yandan da endüstrilerin üretim süreçlerinde ihtiyaç duyduğu insan kaynağına erişimi mümkün kılmaktadır. Şehirlerin ulaşım altyapıları sayesinde sağlanan erişilebilirlikle, insanlar işlerine ve başta sağlık ve eğitim olmak üzere birçok kamu hizmetinden faydalanmak üzere okul, hastane ve diğer kamu kurum ve kuruluşlarına gidebilmekte ve alışveriş yapmak üzere alışveriş merkezlerini ziyaret edebilmektedir. Böylece ulaşım sektörü, ekonominin arz ve talep yönlerinin kritik sektörü olarak belirlenmektedir.

Diğer birçok fiziksel ağda olduğu gibi, ulaşım ağlarında da ciddi verimlilik problemleri bulunmaktadır. Bu problemler, kapasite kısıtının olmadığı birçok durumda farkına varılmadan tolere edilmektedir. Bu durum ulaşım ağları için de geçerlidir. Ancak, giderek, kentleşme ve beraberindeki ekonomik gelişmeler şehirlerde arz edilenden daha fazla kapasite ihtiyacı doğurmakta ve bu durum da ulaşım altyapısı üzerindeki baskıyı artırmaktadır. Bu baskı zar zor yeten (ya da yetersiz) ulaşım altyapısıyla birleştiğinde şehirlerde kapasite eksikliğine neden olmaktadır. Trafik sıkışıklığı problemi, şehirlerdeki altyapı kapasite eksikliğine bir örnektir. Birçok büyük altyapı projesine rağmen artan trafik sıkışıklığı kent içi ulaşımın daha iyi planlanması konusundaki temel ihtiyacı vurgulamaktadır.

Geleneksel fayda ve maliyet analizi yöntemlerine dayalı günümüz ulaşım değerlendirme yaklaşımında, ulaşım politikaları ve ilgili projeler ağırlıklı olarak topluluştırılmış bilgiler kullanılarak değerlendirilmektedir. Bu bağlamda, “bu ulaşım politikasını uygulamanın maliyeti nedir?", "bu ulaşım politikasının uygulanması sonrasında ne kadarlık maliyet tasarrufu sağlayabiliriz?" ve "bu politika maliyet tasarrufu yanında topluma başka hangi faydaları sağlayabilir?" gibi sorular ön plana çıkmaktadır. Her ne kadar bu topluluaştırılmış veriye dayalı yöntemleri kullanmak ve farklı sorulara cevap aramak uygulamada büyük kolaylık sağlasa da, topluluaştırılmış değerler üzerinde çalışmak toplumda karşılaşılabilecek her türlü farklılığı bir kenara atmakta ve bireysel düzeydeki bilgi, topluluaştırma sırasında kaybolmaktadır. Bunun yerine, politika geliştiricilerin, politikaları değerlendirirken bu politikaların hane halkları üzerinde istenmeyen sonuçları olup olmadığını dikkate alan doğru soruları sormaları gerekmektedir: "Önerilen politika bir bölgede oturan düşük gelirli insanların sağlık (ya da eğitim) harcamalarını etkileyecek mi?", "Bu politika belirli bir grup insanın çalışma kararını etkileyecek mi? Bu insanlar bu politikanın uygulanmasından sonra çalışmaktan vaz mı geçecek?" Bu durum, veriyi daha yoğun kullanan modellerin ortaya çıkmasına neden olmaktadır ve bu eğilim günümüz koşullarında artan veri hacmiyle birlikte artarak devam edecektir.

Tez, ulaşım politikalarının uzun vadeli etkilerinin sosyal, ekonomik ve coğrafi farklılıkları dikkate alacak şekilde değerlendirilmesi amacıyla yenilikçi bir modelleme yaklaşımı geliştirmeyi amaçlamaktadır. Böyle bir yaklaşıma neden ihtiyaç duyuyoruz? Hesaplanabilir genel denge modelleri karşılıklı olarak bağımlı piyasalar arasındaki ilişkileri ortaya koyabilen modellerdir. Ancak, bu modeller, sınırlı sayıda (çoğu zaman yalnızca bir) temsili bireyler içermekte ve böylece, farklı bireyler arasındaki heterojenliği ve bu bireylerin politikalar sonucu oluşan davranışsal değişimleri kavrayamamaktadır (Peichl, 2008). Buna karşılık, mikro simülasyon modelleri, insan ve firmaların davranışlarını mikro düzey veri kullanarak modelleyebilmektedir. (Robilliard vd., 2001) Ancak, bu modeller de kısmi denge modelleridir ve yalnızca ekonominin hane halkı tarafını kapsamaktadır (Peichl, 2008). Bu Tezde, farklı düzeydeki bu modeller entegre edilmektedir. Bu bağlamda, geleneksel hesaplanabilir genel denge modelinin geliştirilmesi ile ekonomik birimler farklı özellikleri yansıtacak şekilde ayrıştırılmaktadır. Hane halklarının farklı özelliklerine göre kurgulanan ekonomik model, ayrık seçim teorisine dayalı konut yeri ve ulaşım modu seçim modeli ile entegre edilmektedir. Bu entegrasyon, mevcut literatürde sıkça rastlanılan iki farklı model arasında yakınsama arayan iteratif simülasyonlar şeklinde değil, aynı matematiksel çerçeve içinde "tam entegrasyon" formunda yapılmaktadır. Ekonomik model ve hane halkı konut yeri seçim modelinin yanı sıra, Wardrop'un birinci prensibine[32] dayalı bir ulaşım modeli de bu çerçeve içerisinde kurgulanmıştır. Ulaşım modeli, bu Tezde önerilen yeni bir yöntemle denklem seti haline getirilmiş ve bu sayede CGE modeli içine entegre edilmiştir. Sonuç olarak, üç farklı modelden oluşan entegre bir model ortaya konulmuştur.

Model, temel olarak, hane halklarına ilişkin nüfus sayım ve istatistikleri, bütçe ve yaşam koşulu araştırmaları ve ulaşıma ilişkin hane halklarının ulaşım tercihleri ve yolların trafik yoğunluk bilgilerini kullanacak şekilde tasarlanmıştır.

Çalışma sonucunda ortaya konulan özgün model, insanların kentsel bölgelerdeki hareketlerini etkileyen her türlü müdahalenin (politika değişikliği, altyapı ve toplu taşıma projeleri) uzun vadeli etkilerini farklı gruplar için ortaya koymaktadır. Bu modelin hayata geçirilmesiyle, ulaşım alanında ortaya konulacak politikaların ve bu politikalarla ilgili altyapı projelerinin toplumun farklı kesimlerine etkileri açıkça ortaya konulabilmektedir. Böylece, ulaşımın özellikle toplumun farklı kesimleri (örneğin dışlanmış ya da dışlanma potansiyeli yüksek) üzerindeki etkileri anlaşılabilecek ve daha kapsayıcı ulaşım politikalarının oluşturulması önündeki değerlendirme enstrümanı eksikliği giderilebilecektir. Bu açıdan bakıldığında, önerilen model, "sürdürülebilir ulaşım" çerçevesinde kritik öneme sahip olan "alternatif ulaşım politikalarının" tespitinde ve uygulamasında etkin bir karar destek aracı olarak kullanılabilecektir.

Ortaya konulan model, dört bölgeli küçük bir kent için yapay veriler ve farklı politikalar kullanılarak test edilmiştir. Daha sonra, LTDS 2014 verileri kullanılarak, Londra'da yapımı planlanan Crossrail 2 projesinin etki analizi yapılmıştır. Buna ilişkin sonuçlar, bu Özetin Senaryo Analizi bölümünde verilmektedir.

Bu araştırmanın en önemli özgün değeri, insan davranışlarını dikkate alan ve mikro düzeyde toplulaştırılmamış veri kullanan hane halkı konut yeri ve ulaşım modu seçim modellerini bir hesaplanabilir genel denge modeli içinde birleştirmesidir. Daha önceden belirtildiği üzere, bu birleştirme işlemi tam entegrasyon prensibi ile gerçekleştirilecektir. Bu sayede, gereksiz sayıda iterasyon işlemleri yerine, her iki

---

[32] *Wardrop'un birinci prensibi*: Kişilerin çoğunlukla, kendisine en düşük maliyeti sunan; daha net bir ifade ile, seyahat süresi, maliyet, güvenilirlik ve güvenlik gibi hizmet düzeyi bileşenlerinin meydana getirdiği en düşük yararsızlığı sunan türü seçmesi.

model aynı problem içerisinde bir defada çözümlektedir. Araştırmanın bir diğer özgün yanı ise, bölgeler arası ulaşım sürelerini ve maliyetlerini trafik sıkışıklığı etkilerini dikkate alarak hesaplayan bir trafik modelinin önerilen entegre model yapısı içine dahil edilmesidir. Literatürdeki çalışmalara bakıldığında, bahsedilen üç farklı modelin birlikte entegre edildiği bir çalışma bulunmamaktadır. Bu nedenle, bu çalışma, ulaşım politikalarının değerlendirilmesi amacıyla son derece kompakt yapıda bir model çerçevesi sunmaktadır.

Bu çalışmanın bir diğer özgün yanı ise hane halkı düzeyinde veri kullanılarak makroekonomik analizler yapılmasıdır. Bu açıdan bakıldığında, başta nüfus sayımı gibi hane düzeyinde yapılan birçok araştırmanın makroekonomik modeller içinde haneler arasındaki ayrımı gözetecek şekilde kullanılması yönünde önemli bir örnek oluşturmaktadır. Böylece, ekonomik birimler düzeyinde elimizde var olan birçok ayırt edici önemli bilginin ekonomik modeller içinde kullanılması ve toplumun her kesimini (özellikle dezavantajlı grupları) gözeten daha doğru politikalar geliştirilmesi sağlanacaktır.

Çalışma sonucunda ortaya konulan entegre model sistemi, ulaşım politikalarının uzun vadeli ekonomik, sosyal ve coğrafi etkilerini ortaya koyması açısından önemli bir örnektir. Bu model sistemi kullanılarak, ulaşımla ilgili birçok farklı politikanın etki analizinin yapılması mümkün olacaktır.

LİTERATÜR TARAMASI

Son yıllarda, hesaplanabilir genel denge modellerinin ulaşım alanında, özellikle ulaşım politikalarının etki analizinde kullanımı artmaktadır (Chicago kordon ücretlendirmesi (cordon tolling) analizi için Anas ve Hiramatsu (2013), Paris toplu taşıma analizleri için Anas (2013a), Tokyo trafik sıkışıklığı ücretlendirme sistemleri analizi için Sato ve Hino (2005)). Geleneksel fayda ve maliyet analizlerine (CBA – cost-benefit assessment) dayalı modellerin ulaşımdan kaynaklı dışsallıkların içselleştirilmesi ve etkilerin ekonomik birimler arasında dağıtımı konularında yetersiz kalması, bu eğilimi daha iyi açıklamaktadır (Robson ve Dixit, 2015). Ulaşımın ekonomi içerisindeki merkezi rolü düşünüldüğünde, bu zayıflıkların görmezden gelinmesi mümkün olmamaktadır. Bundan dolayı, ulaşım alanındaki politika ve projelerin doğrudan etkilerinin yanı sıra dolaylı etkilerinin de değerlendirilmesi imkanı sağlayan daha kapsayıcı bir ekonomik analiz aracı olan hesaplanabilir genel denge modellerinin önemi giderek artmaktadır.

Ulaşım alanında kullanılan hesaplanabilir genel denge modellerine bakıldığında, bu modellerin iki ana başlıkta kullanılabildiği görülmektedir:

1) Bölge ölçeğinde modeller: Daha çok üretim faaliyetlerine odaklanılan ve ulaşımın bir sektör olarak ele alındığı modeller

2) Kent ölçeğinde modeller: Ekonomik karar vericilerin (özellikle hane halkları) ayrık seçim kararlarının ele alındığı modeller

Bölge-ölçeğinde modeller:

Bröcker ulaşım alanında hesaplanabilir genel denge modellerinin kullanımı konusunda önemli katkılar sunmuştur. Bu katkıların başında, Bröcker'in (1998) modelinde, geleneksel ekonomik birimler (hane halkları ve firmalar) yanı sıra ulaşım aktivitelerinden sorumlu ayrı "ulaşım birimlerinin" tanımlanması gelmektedir. Bu modelde, ulaşımın, hane halklarının hareketliliğiyle ilgili değil yalnızca firmaların faaliyetleriyle ilgili bir konu olduğu varsayılmıştır. Bununla birlikte, bir başka modelinde Bröcker (2002), hane halklarının yolculuklarını da modele dahil etmiştir. Bu modellerden farklı olarak, Bröcker vd. (2004), ulaşım aktiviteleri ve bu aktivitelere bağlı maliyetleri tamamen farklı bir yaklaşımla ele almış, ulaşım maliyetlerini Samuelson'ın (1954) buz dağı modeline dayandırmıştır. Bu modelde, ulaşım maliyetleri mesafenin doğrusal bir fonksiyonu olarak tanımlanmaktadır. Bu yaklaşımın, Bröcker vd.'nin (2010) modelinde de benimsendiği görülmektedir. Bröcker'in (2002) modelinden etkilenen Zhu vd. (2012) bazı ulaşım (HS2 yapımı ve A11 yolunun genişletilmesi) ve arazi kullanım (yeşil kuşağın esnetilmesi) politikalarının geniş ekonomik etkilerini analiz etmek üzere statik bir hesaplanabilir genel denge modeli kullanmıştır.

Oosterhaven ve Knaap (2003), Groningen şehri ve Schiphol Havalimanı arasındaki 6 farklı demiryolu bağlantısını test etmek amacıyla, Knaap ve Oosterhaven'ın (2000) RAEM hesaplanabilir genel denge modelini kullanmıştır. Yazarlar bu çalışmayı birkaç küçük değişiklikle Knaap ve Oosterhaven'ın (2011) çalışmasında tekrar etmiştir.

Birçok bölgesel modelden farklı olarak, Kim vd. (2004), ulaşımı erişilebilirliğe etkisini dikkate almış ve Güney Kore'deki otoyol projelerinin ekonomik büyüme ve bölgesel farklılıklar perspektifinden değerlendirilmesi amacıyla, dinamik bir hesaplanabilir genel modelini bölgelerdeki erişilebilirlik değişimlerini ölçen bir ulaşım modeliyle entegre etmiştir.

Hane halklarının ulaşıma hizmetlerine talebi, Berg'in (2007) tarafından, hane halklarının ve firmaların enerji ve çevre vergilerini ödemekle yükümlü oldukları enerji perspektifli bir modelde ele alınmıştır.

Verikios ve Zhang (2015), Avustralya'da hayata geçirilen kent içi ulaşım reformunun doğrudan ve dolaylı etkilerinin değerlendirilmesi amacıyla, hesaplanabilir genel denge modeliyle birlikte bir mikro simülasyon modelini kullanmış ve kent içi ulaşım reformunun hane halkları üzerine etkileri farklı gruplar için hesaplanmıştır. Bu çalışmada, kent içi ulaşım ayrı bir ekonomik sektör olarak yer almıştır.

Kent-ölçeğinde modeller:

Firma aktiviteleri ve ticaret konularına odaklanan bölgesel modellerden farklı olarak, kent ölçeğindeki modeller daha çok hane halklarının ulaşımla ilgili davranışlarına odaklanmaktadır. Bu bağlamda, hane halklarının karşılaştıkları konut yeri veya iş yeri gibi ayrık seçimler, bu modellerin temel odak noktaları durumundadır. Bu alanda araştırma yapanlar arasında, ayrık seçim modellerinin ulaşım alanında uygulanması konusunda ilk örnekleri sunan Alex Anas ön plana çıkmaktadır. Anas (1982), başta ulaşım olmak üzere birçok kentsel konuların analizinde, hesaplanabilir genel modeli ve ayrı seçim modelini birlikte kullanmıştır. Ayrıca, Alex Anas, farklı dönemlerde beraber çalıştıkları bir dizi araştırmacıyla birlikte, metropol alanlarda uygulanan politikalarının etkilerini değerlendiren bir bölgesel hesaplanabilir genel denge modeli olan RELU-TRAN (Regional Economy, Land Use and Transportation Model) modelini geliştirmiştir. [Anas ve Kim (1996), Anas ve Xu (1999), Anas ve Liu (2007), Anas ve Hiramatsu (2012), Anas (2013a), Anas (2013b), Anas ve Hiramatsu (2013)].

Horridge (1994) kent içi ulaşım problemini, ayrık seçim teorisinin temel çıktılarından faydalanarak, oldukça basit ama etkili bir yöntem kullanarak ele almıştır. Bu bağlamda, Avustralya'nın Melbourne şehrinde uygulanan çeşitli senaryoların etkilerini analiz etmek üzere kent ölçeğinde bir hesaplanabilir genel denge modeli önerilmiştir. Bu model çerçevesinde, konut yeri ve iş yeri çift seçimlerinin multinomial logit (MNL) olasılıkları, her bir seçim çiftinin pazar paylarını hesaplamak için kullanılmaktadır. Böylece, bu toplulaştırılmış değerler, hane halklarının davranışlarını yansıtacak şekilde, hesaplanabilir genel denge modeli içerisinde bir parametre olarak kullanılmaktadır. Bu toplulaştırma prosedürü Magnani ve Mercenier (2009) tarafından da irdelenmiştir. Ayrık seçim teorisine dayalı kısmi denge modelleri ile hesaplanabilir genel modellerinin entegre edilmesi amacıyla, heterojen özellikte bireylerin temsili ekonomik birim içerisinde toplulaştırıldığı "tam toplulaştırma" (exact aggregation) yöntemi önerilmiştir. Bir iş gücü piyasası için yapılan örnek çalışmada, bazı özel koşulların sağlanması durumunda, istatistiksel olarak benzer ve bağımsız bireylerden oluşan büyük bir veri setine ilişkin ayrık seçim olasılıklarının toplulaştırılmasının "sabit dönüşüm esnekliği" (CET – Constant Elasticity of Transformation) fonksiyonuna sahip tek bir ekonomik birimin optimizasyonu sonucu elde edilen toplu işgücü arz fonksiyonuna eşit olduğu gösterilmiştir.

Sato ve Hino (2005), Tokyo'da uygulanması planlanan trafik sıkışıklığı ücretlendirme sisteminin arazi kullanımı, bölgesel iktisat ve ulaşım üzerine olan uzun vadeli etkilerinin değerlendirilmesi amacıyla hesaplanabilir genel denge modeli kullanmıştır. Bu modelde, hane halklarının ve firmaların yer seçim olasılıkları logit modelleri kullanılarak hesaplanmaktadır. Önerilen hesaplanabilir genel denge modeli, yolculuk tercihlerinin modellenmesi amacıyla, genel bir 4-adımlı yolculuk modeli ile entegre edilmiştir.

Rutherford ve van Nieuwkoop (2011), İsviçre'nin Zürih şehrine doğru olacak yüksek profilli işgücünün etkilerini değerlendirmek amacıyla kent içi ulaşımı kapsayan bir hesaplanabilir genel denge modeli önermiştir. Bu modelde, basit bir ekonomi modellenmiş ve ekonomik birim olarak hane halkları ve üretici firmalar yer almıştır.

Truong ve Hensher (2012), Avustralya'nın Sydney şehrinde yapılacak bir ulaşım projesinin uzun vadeli ekonomik etkilerini değerlendirmek üzere, ayrık seçim teorisine dayalı modeller ile "kesintisiz talep" (continuos demand) modellerinin hesaplanabilir genel denge modeli çerçevesinde entegre edildiği bir yöntem önermiştir.

Yukarıda bahsedilen çalışmalar, ulaşımın hesaplanabilir genel denge modeli çerçevesinde çok farklı yaklaşımlarla ele alındığını göstermesi açısından önemlidir. Ulaşım, bölgesel modellerde bir hizmet sektörü ya da üreticiler için katlanılması gereken bir maliyet olarak ele alınırken, kentsel modellerde kentlerdeki erişilebilirliği ve dolayısıyla insanların mekan seçimlerini etkileyen çok önemli bir faktör olarak ele alınmaktadır. Hakikaten de, ulaşımın en büyük etkisi bir sektör olarak ya da bir maliyet olarak parasal konularda değil ekonomik birimlere sağlanan erişilebilirlikte yatmaktadır. Erişilebilirlik, mekânsal analizler düşünüldüğüne, insanların karar verme süreçlerinde merkezi bir rol üstlenmektedir. Bu noktada, sorulması gereken bir soru: "Kimin ya da hangi bölgenin erişilebilirliğini dikkate almalıyız?" Bu kritik bizleri bir noktaya götürecektir: insanlar arasındaki farklılıklar. Ulaşım, özellikle kent içi ulaşım, düşünüldüğünde, klasik hesaplanabilir genel denge modellerinde yer alan temsili ekonomik birimler erişilebilirlik konusunun yeterince irdelenmesi konusunda, doğal olarak, yetersiz kalacaktır. İşte bu noktada, ayrık seçim teorisine dayalı davranışsal modeller, hane halkları arasındaki heterojenliği kapsama konusunda önemli bir potansiyel barındırmaktadır. Ancak, farklı düzeyde modellerin entegrasyonu ise, modelcilerin aşması gereken önemli bir problem olarak ortada durmaktadır.

MODELLEME YAKLAŞIMI

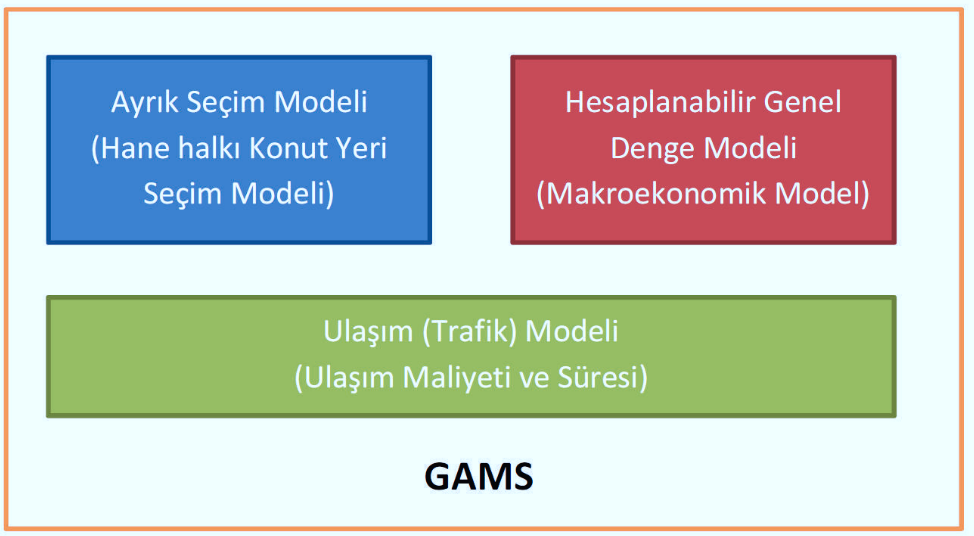
Ulaşım iktisadi ve sosyal faaliyetlerin hayata geçirilmesinde önemli bir yere sahiptir. Yeterli ulaşım altyapısı olmayan bölgelerin diğer bölgelere göre daha az gelişme potansiyeline sahip olması konusunda geniş bir zaman dilimine yayılmış oldukça fazla sayıda araştırma bulunmaktadır. Bu bağlamda, uç bir örnek olarak, Adam Smith, ünlü Milletlerin Zenginliği kitabında, taşımacılık maliyetleri konusuna da değinmiş ve denize kıyısı olan bölgelerin daha hızlı geliştiğini ifade etmiştir. Hakikaten de, yeterli ulaşım altyapısı olmayan ülkelerde (ya da bölgelerde) iyi işleyen piyasalardan söz etmek mümkün değildir. Ulaşım altyapısı bir yandan insanlar ve endüstriler tarafından talep edilen mal ve hizmetlerin iletimi için gerekli iletim kanallarını sağlarken bir yandan da endüstrilerin üretim faaliyetlerinde ihtiyaç duyduğu insan kaynağına erişimi sağlamaktadır.

Ulaşım altyapıları arasında kent içi ulaşım altyapısı etki ettiği alan çeşitliliği ve insan sayısı bakımından özel bir konuma sahiptir. Doğal bir süreç olan şehirleşme ve kent ekonomilerindeki gelişmeler sonucu ortaya çıkan talep kapasite artışlarıyla çoğu zaman karşılanamamakta ve kent içi ulaşım altyapısı üzerindeki baskı artmaktadır. Bu durum beraberinde "trafik sıkışıklığı" problemini getirmektedir. İktisadi açıdan trafik sıkışıklığı iki açıdan önemlidir. Öncelikle, insanların (çeşitli nedenlerle) ısrarla aynı saatlerde trafiğe çıkmaları ve diğer insanlar üzerinde yarattıkları sosyal maliyet ciddi bir piyasa başarısızlığı anlamına gelmektedir (Krugman, 2013). Bunun yanı sıra, trafik sıkışıklığı sonucu artan ulaşım süreleri ve maliyetler bölgelerin "erişilebilirliğini" ve arazi kullanımını büyük ölçüde etkilemektedir. Bu da insanların ve firmaların yer seçimlerinde kritik öneme sahiptir. Bundan dolayı, kent içi ulaşım politikalarının iktisadi olarak dikkatlice irdelenmesi gerekmektedir.

İncelenen ulaşım politikasının, bir yandan ekonominin geneline etkisini gözlemlemeyi sağlayan makroekonomik araçlara ihtiyaç duyulurken bir yandan da farklı grupların politika davranış değişikliklerini tahmin edebilecek ve insanlar arasındaki farklılığı dikkate alacak mikro simülasyon araçlarına ihtiyaç vardır. McFadden (1977) tarafından "ayrık seçim teorisi (discrete choice theory)" üzerine yapılan çalışmalar, farklı grup insanların belirli şartlar altında yaptıkları seçimlerin modellenmesi konusunda bir dönüm noktası olmuştur. Bu modelleme aracı sayesinde, bireylerin istihdam piyasasına dahil olup olmama kararı, yapacakları yolculuklar için hangi ulaşım araçlarını seçecekleri, nerede oturacakları, nerede çalışacakları gibi birçok "ayrık karar" rahatlıkla modellenebilir hale gelmiştir. Bu bağlamda, ayrık seçim modellerinde, karar vericilerin alternatifler arasında yaptıkları değerlendirme sonucu verdikleri kararın sonucu ayrık bir değerdir. Ancak, daha önce de belirtildiği üzere, ulaşım politikalarının geniş etkilerini ortaya koymak için makroekonomik modellerle ayrık seçim teorisine dayalı mikro düzey modellerin entegre edilmesine ihtiyaç bulunmaktadır. Bu hibrit yapı karar vericiler arasındaki heterojenliği (mikro) ve farklı piyasalar arasındaki ilişkileri (makro) birlikte ele almaktadır. Farklı düzeylere sahip bu modellerin entegre edilmesi ise, başlı başına aşılması gereken güç bir problem olarak ortaya çıkmaktadır. Bu problemin aşılmasında kritik öneme sahip konu, modellerin hangi değişkenleri dışsal (exogenous) olarak kabul edip dışarıdan alması hangi değişkenleri ise içsel (endogenous) olarak kabul edip model içinde çözmesidir. Farklı modeller arasında girdi-çıktı ilişkisine dayalı bir değişken alışverişi yapısı oluşturulabilirse, bu modellerin entegre edilebilmesi mümkün olabilmektedir (Horridge, 1994).

Farklı modellerin entegrasyonu konusunda mevcut literatüre bakıldığında, temel olarak, iki farklı yaklaşımın olduğu görülmektedir. Bu yaklaşımlardan ilki, modeller arasında değişken alışverişi yapısı oluşturulduktan sonra, modellerin sırasıyla çalıştırılması ve bu iteratif işlemlerin model sonuçlarında anlamlı bir değişiklik olmayıncaya kadar devam ettirilmesine dayanmaktadır. Bir diğer yaklaşım ise, farklı modellerin aynı matematiksel çerçeve içerisine modellenmesi ve modeller arası parametre transferinin bu çerçeve içerisinde yapılmasına dayalı "tam entegrasyon" yaklaşımıdır.

Bu tez kapsamında, kent içi ulaşım politikalarının etraflı bir şekilde incelenmesi amacıyla hibrit yapıda bir model kurulmuştur. Bu hibrit yapı karar vericiler arasındaki heterojenliği (mikro) ve farklı piyasalar arasındaki ilişkileri (makro) birlikte ele almaktadır. Bu bağlamda, ulaşım politikaları sonucu bireylerin davranışlarındaki değişiklikleri modellemek amacıyla ayrık seçim teorisine dayalı bir "hane halkı konut yeri seçimi modeli" geliştirilmiş ve bu model bir hesaplanabilir genel denge modeliyle entegre edilmiştir. Ayrıca, aynı matematiksel çerçeve içerisinde, bölgelerarası ulaşım maliyeti ve süre matrislerini oluşturan bir trafik modeli, Wardrop'un birinci prensibine dayalı olarak "Trafik Atama Problemi (TAP - Traffic Assignment Problem)" formatında modellenmiştir. Daha sonra, TAP, tez kapsamında önerilen yeni bir yöntemle denklem seti haline getirilmiş ve diğer iki modelle entegre edilebilir hale gelmiştir. Bu üç farklı model, GAMS (General Algebraic Modeling Solver) modelleme aracı kullanılarak aynı problem içinde modellenmiştir. Şekil 1'de görüldüğü üzere, hesaplanabilir genel denge modeli, hane halkı konut yeri seçim modeli ve trafik modeli aynı matematiksel çerçeve içinde entegre edilmektedir.



Şekil 1 Entegrasyon Yaklaşımı

Modeldeki temel aktörlerden olan hane halkları 4 farklı indekse göre gruplanmaktadır: (i) konut yeri (i) (ii) iş yeri lokasyonu (w) (iii) ulaşım aracı tercihi (m) ve (iv) beceri seviyesi (g). Bir şehirdeki tüm hane halkları bu indeksler kullanılarak gruplandırılmaktadır. Modelde hane halklarının barınma ihtiyaçları diğer tüketim araçlarından ayrı tutulmaktadır. Bu bağlamda, hane halkları barınma ve diğer tüketim malzemelerini ve sabit ikame esnekliği (CES - constant elasticity of substitution) fayda fonksiyonunu kullanarak fayda elde etmektedir. Aynı zamanda, oturulan bölgeye bağlı bir pozitif fayda ve ev-iş arasındaki yolculuklar için harcanan süreden dolayı bir negatif fayda hane halklarının fayda fonksiyonu içine girmektedir. Hane halklarının, ekonomideki sermaye ve konut stokunun da sahibi olduğu kabul edilmektedir. Bundan dolayı, hane halklarının, sahip olunan sermayeyi firmalara ve konutları da diğer hane halklarına kiralayarak ücret dışı gelir elde ettikleri varsayılmaktadır.

İstihdam piyasasına, her bir haneden en fazla bir iş gücü arz edilmektedir. Bu durumda, bazı haneler, işgücüne katılmış ve bazı haneler de (emekli, işsiz vb.) ise katılmamış olmaktadır. Arz edilen iş gücü iki çeşittir: (i) nitelikli iş gücü ve (ii) niteliksiz iş gücü. Bu farklı tip iş güçleri ekonomik faaliyetlerin her birine farklı oranda katkı sağlamakta ve her bir iş gücü türü için ekonomide farklı bir fiyat seviyesi belirlenmekte olduğu kabul edilmektedir. Bu sayede, haneler arasındaki gelir farklılıkları incelenebilecek ve ulaşım politikalarının farklı gelir seviyesine sahip gruplar üzerindeki etkileri açıkça ortaya konabilecektir.

Oluşturulan modelde hane halklarının yalnızca konut yeri ve ulaşım aracı tercihleri modellenmekte olup, çalışan insanların iş yerlerinin sabit kaldığı kabul edilmektedir. Ulaşım aracı olarak, özel araç, toplu taşıma (sıkışıklıktan etkilenmeyen – metro, BRT, tahsisli otobüs yollarında seyreden araçlar), toplu taşıma (sıkışıklıktan etkilenen – otobüs, dolmuş vs.) ve motorsuz ulaşım (bisiklet, yürümek) alternatifleri kullanılmaktadır. Tahsisli otobüs yollarında ilerlemeyen otobüsler için ayrı durak yerlerinin olduğu ve bu sayede trafik akışını etkilemedikleri varsayılmaktadır.

Model Bileşenleri:

1 - **Ayrık seçim teorisine dayalı hane halkı konut yeri seçim modeli** (aynı zamanda ulaşım modu seçim modeli) her bir hane halkı için bölge seçimlerine ilişkin bir dizi olasılık seti oluşturmaktadır. Ayrık seçim teorisine göre (diğer modelleme yöntemlerinde de olduğu gibi) karar vericilerin faydalarını maksimize edecek şekilde karar verdikleri kabul edilmektedir. Ancak, bu teoride, karar vericilerin fayda fonksiyonunun gözlemlenebilir bileşeni yanında bir de gözlemlenemeyen ve karar vericiler arasında heterojenliği sağlayan stokastik bir bileşenden oluştuğu kabul edilir. Böylece, her hangi bir karar verici n, J farklı alternatif arasından aşağıdaki fayda fonksiyonunu kullanarak karar verir:

$$U_{ni} = V_{ni} + \varepsilon_{ni} \qquad \left(i = 0, 1, 2..., J\right) \tag{1}$$

Burada, V_{ni} araştırmacı tarafından gözlemlenen "temsili faydayı" (representative utility) ifade ederken, ε_{ni} ise bu fayda tarafından içerilemeyen stokastik bileşeni ifade etmektedir (Train, 2002:19). Böylece, $U_{ni} > U_{nj} \left(i \neq j\right)$ durumunda, karar verici n, farklı alternatifler arasından i alternatifini seçecektir. Bu durumda, karar vericinin i alternatifini seçme olasılığının, bir dizi matematiksel işlemden sonra aşağıdaki *multinomial logit* (MNL) olasılıkları formunda hesaplanması mümkün olmaktadır:

$$P_{ni} = prob\left[U_{ni} > U_{nj}, \forall j \neq i\right] = \frac{e^{\mu V_{ni}}}{\sum_{j=1}^{J} e^{\mu V_{nj}}} \tag{2}$$

Hane halklarının barınma ve diğer tüketim ürünlerinin kullanımından elde ettikleri faydanın yanı sıra, konut yeri olarak seçtikleri bölgeden bir fayda elde ettikleri ve ev-iş arası yolculuklar için harcanan zamandan dolayı da negatif fayda oluştuğu kabul edilirse kullanılan fayda fonksiyonu aşağıdaki şekilde ifade edilebilir.

$$U_{iwmg}\left(d,c\right)=\underbrace{\left[\sum_{k=1}^{n}\alpha_{iwmg}^{k}c_{iwmg,k}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right]^{1/\rho}+\Psi_{i}-\gamma_{iwmg}\tau_{iwm}}_{V_{iwmg}}+\varepsilon_{iwmg} \quad (3)$$

Yukarıdaki denklemde *i* oturum bölgesi, *w* çalışma bölgesi, *m* ulaşım modu ve *g* hane halkı heterojenlik endeksini (örneğin eğitim seviyesi) temsil etmektedir. Buna göre, hane halklarının *d* büyüklüğünde bir konut ve *c* miktarında tüketim ürünleri harcaması yaptıkları kabul edilmektedir. Burada *k* parametresi sektörleri temsil ederken *n* de ekonomideki sektör sayısını vermektedir. Bu tüketim sonucunda CES fayda fonksiyonu formunda fayda sağladığı görülmektedir. Aynı zamanda, belirli bir bölgede oturmanın Ψ_i büyüklüğünde fayda sağladığı ve ev-iş arası yapılan yolculukların da γ_{iwmg} ölçeğinde negatif fayda oluşturduğu kabul edilmektedir. Denklemde *α* paylaşım parametresidir. Konut ve tüketim harcamaları arasındaki ikame parametresi *σ* ve *ρ* arasındaki ilişki *ρ = (σ-1)/ σ* olarak ifade edilebilir.

Yukarıdaki fayda fonksiyonu ve MNL olasılık formülü kullanılarak, herhangi bir hane halkının belirli bir *i* bölgesini konut yeri olarak ve belirli bir *m* ulaşım modunu da ev-iş arası yolculuklarda tercih edilen ulaşım modu olarak seçmesi olasılığı şu şekilde hesaplanabilir:

$$P_{w,g}\left(i,m\right)=\frac{\exp\left(\left[\sum_{l=1}^{n}\alpha_{iwmg}^{l}c_{iwmg,l}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right]^{1/\rho}+\Psi_{i}-\gamma_{iwmg}\tau_{iwm}\right)}{\sum_{j}\sum_{m'}\exp\left(\left[\sum_{l=1}^{n}\alpha_{jwm'g}^{l}c_{jwm'g,l}^{\rho}+\alpha_{jwm'g}^{h}d_{jwm'g}^{\rho}\right]^{1/\rho}+\Psi_{j}-\gamma_{jwm'g}\tau_{jwm'}\right)} \quad (4)$$

Denklemde (*i,w,m*) ile endeksli τ, *i* yerleşim bölgesinden *w* çalışma gölgesine *m* ulaşım modunun kullanılması durumundaki seyahat süresini temsil etmektedir. Buradaki olasılık değerleri ve veri setinden dışsal olarak gözlemlenen hane halkları sayıları kullanılarak, her bir yerleşim bölgesi (*i*) ve ulaşım modu (*m*) çiftlerinin payları aşağıdaki basit formül kullanılarak hesaplanabilmektedir. Bu formül, bir bakıma, alternatiflerin "pazar paylarını" hesaplamaktadır. Buna göre, $N_{i,m}\left(w,g\right)$ *w* bölgesinde çalışan ve *g* heterojenlik seviyesine sahip olanlar arasından *i* bölgesinde oturup *m* ulaşım modunu kullananların sayısını verecektir:

$$N_{i,m}(w,g)=P_{w,g}(i,m)\cdot N(w,g)$$

$$=\frac{\exp\left(\left[\sum_{l=1}^{n}\alpha_{iwmg}^{l}c_{iwmg,l}^{\rho}+\alpha_{iwmg}^{h}d_{iwmg}^{\rho}\right]^{1/\rho}+\Psi_{i}-\gamma_{iwmg}\tau_{iwm}\right)}{\sum_{j}\sum_{m'}\exp\left(\left[\sum_{l=1}^{n}\alpha_{jwm'g}^{l}c_{jwm'g,l}^{\rho}+\alpha_{jwm'g}^{h}d_{jwm'g}^{\rho}\right]^{1/\rho}+\Psi_{j}-\gamma_{jwm'g}\tau_{jwm'}\right)}N(w,g) \qquad (5)$$

Ayrık seçim teorisine dayalı hane halkı konut yeri seçim modülünün temel çıktısı olan $N_{i,m}(w,g)$ değişkeni, entegre yaklaşımının ikinci modülünü oluşturan hesaplanabilir genel denge ve ulaşım modüllerine girdi olarak kullanılmaktadır.

2- Entegre modelleme yaklaşımının ikinci modülü, **hesaplanabilir genel denge modelidir**. Hesaplanabilir genel denge modelinin, hane halkları ve firmalar tarafından oluştuğu kabul edilmektedir. Bu modelde hane halklarının aşağıdaki Lagrange eşitliği ile faydalarını maksimize ettiği varsayılmaktadır:

$$\mathcal{L}(d,c,\lambda)=\left[\sum_{k=1}^{n}\alpha_{g}^{k}c_{iwmg,k}^{\rho_g}+\alpha_{g}^{h}d_{iwmg}^{\rho_g}\right]^{1/\rho_g}-\gamma_{g}\tau_{iwm}+\lambda\left[w_{g}-r_{i}d_{iwmg}-\sum_{k=1}^{n}p_{k}c_{iwmg,k}-\kappa_{iwm}\right] \qquad (6)$$

Yukarıdaki denklemde *w* hane halkı gelirini, *r* konut kira bedelini, *p* tüketim ürünlerinin komposit fiyatını ve κ_{iwm} de ulaşım moduna göre bölgeler arası ulaşım maliyetini ifade etmektedir.

Yukarıda temsil edilen maksimizasyon probleminin birincil derece koşulları:

$$(d) \quad \alpha_{g}^{h}\left[\sum_{k=1}^{n}\alpha_{g}^{k}c_{iwmg,k}^{\rho_g}+\alpha_{g}^{h}d_{iwmg}^{\rho_g}\right]^{(1-\rho_g)/\rho_g}d_{iwmg}^{\rho_g-1}-\lambda r_{i}=0 \qquad (7)$$

$$(c) \quad \alpha_{g}^{k}\left[\sum_{k=1}^{n}\alpha_{g}^{k}c_{iwmg,k}^{\rho_g}+\alpha_{g}^{h}d_{iwmg}^{\rho_g}\right]^{(1-\rho_g)/\rho_g}c_{iwmg,k}^{\rho_g-1}-\lambda p_{k}=0 \quad \forall k \qquad (8)$$

$$(\lambda) \quad w_{g}-r_{i}d_{iwmg}-\sum_{k=1}^{n}p_{k}c_{iwmg,k}-\kappa_{iwm}=0 \qquad (9)$$

olmak üzere hane halkı seçimlerini (*c* ve *d* değişkenleri) belirlemede kullanılır. Böylelikle herhangi bir i yerleşim bölgesindeki toplam sektörel tüketim talebi ve toplam konut talebi belirlenebilmektedir:

$$D_{i}=\sum_{w}\sum_{m}\sum_{g}d_{iwmg} \quad \forall i \qquad (10)$$

$$C_k = \sum_i \sum_w \sum_m \sum_g c_{iwmg,k} \qquad \forall k \tag{11}$$

Hane halkı karar değişkenleri **ayrık seçim teorisine dayalı hane halkı konut yeri seçim modülünün** girdileri olarak (5) No.lu denklemde kullanılmaktadır.

Model kapsamında, firmalar ise aşağıdaki katma değer fonksiyonunu ve üretim faktörlerini (sermaye ve iş gücü) kullanarak veri üretim miktarı için maliyetlerini minimize etmektedir:

$$VA_l = v_l \cdot y_l = \phi_l \left(\beta_l K_l^{\frac{(\sigma-1)}{\sigma}} + \left(1-\beta_l\right) L_l^{\frac{(\sigma-1)}{\sigma}} \right)^{\frac{\sigma}{(\sigma-1)}} \tag{12}$$

Burada, her bir *l* sektörü için, ϕ toplam faktör verimliliğini, β CES üretim fonksiyonu faktör paylaşım katsayısı, *L* kompozit iş gücü faktörünü, *K* sermaye faktörünü ve σ de faktörler arası ikame esnekliğini ifade etmektedir. İş gücünün iki farklı grup tarafından sağlandığı kabul edilmektedir: (i) nitelikli (eğitim seviyesine göre) iş gücü ve (ii) niteliksiz iş gücü. Böylece, *LS* nitelikli, *LU* da niteliksiz işgücünü temsil etmek üzere, her bir sektör için kompozit iş gücü talebi aşağıdaki formda ifade edilmektedir:

$$L_l = \left(\beta_l^L LS_l^{\frac{\left(\sigma^L-1\right)}{\sigma^L}} + \left(1-\beta_l^L\right) LU_l^{\frac{\left(\sigma^L-1\right)}{\sigma^L}} \right)^{\frac{\sigma^L}{\left(\sigma^L-1\right)}} \tag{13}$$

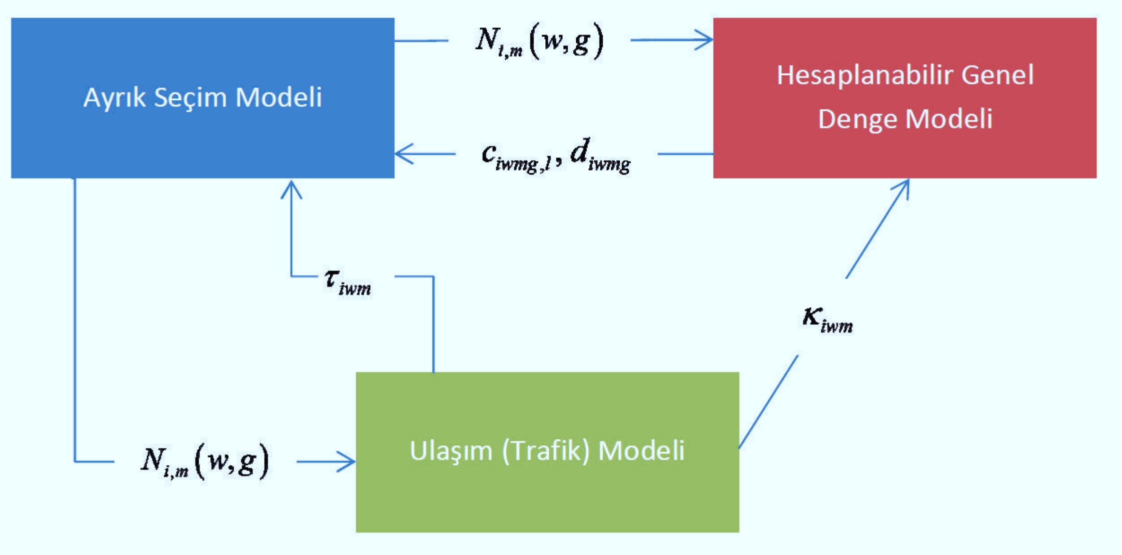
Ekonomide toplam kompozit işgücü talep/arz denge koşulu ücretlerin belirleyicisi olarak hane halkı gelirlerine etki edecektir.

3- Ulaşım modeli, *Wardrop'un birinci prensipi* olarak bilinen ve yol ağını kullanan bireylerin "bireysel denge" noktalarını bulan yaklaşım esas alınarak GAMS platformunda geliştirilmektedir. Bu model, insanların bölgeler arasında en kısa sürede yolculuk yapmalarını imkan veren seçimleri yapmalarını sağlayan ve insanların seçimleri oluşan trafik yoğunluğunu dikkate alan bir yapıda modellenmektedir. Trafik yoğunluğu, yolculuk sürelerini uzatan bir unsur olarak ele alınmaktadır. Bu bağlamda, LeBlanc vd. (1975) tarafından önerilen, toplam ulaşım süresinin yolun uzunluğuna bağlı sabit bir yolculuk süresi ile yolun yoğunluğuna bağlı olarak değişen yolculuk süresi bileşenlerinin fonksiyonu olarak tanımlandığı eşitlik kabul edilmektedir:

$$t(a) = \mathrm{A}(a) + \mathrm{B}(a)\left[\frac{q(a)}{Q(a)}\right]^4 \qquad \forall a \in A \tag{14}$$

Burada $t(a)$ yol ağında bulunan a yolunu geçmek için gerekli süre, $\mathrm{A}(a)$ yolun uzunluğuna bağlı sabit yolculuk süresi, $\mathrm{B}(a)$ yoğunluk katsayısı, $q(a)$ yoldaki anlık yoğunluk ve $Q(a)$ yolun kapasitesini ifade etmektedir.

Farklı modellerin aynı çatı altında entegrasyonu, modeller arasında bazı parametrik değerlerin paylaşımıyla mümkün olmaktadır. Şekil 2'de Tez kapsamında kurgulanan entegrasyona ilişkin durum şematik olarak verilmiştir. Burada, $N_{i,m}(w,g)$ w bölgesinde çalışan ve g beceri seviyesine sahip olanlar arasından i bölgesinde oturup m ulaşım modunu kullananların sayısını, $c_{iwmg,l}$ hane halklarının her bir sektöre ilişkin tüketim miktarı, d_{iwmg} hane halklarının konut harcamaları, τ_{iwm} ulaşım modlarına bağlı olarak bölgeler arasında ulaşım süreleri ve κ_{iwm} ulaşım modlarına bağlı ulaşım maliyetlerini ifade etmektedir.

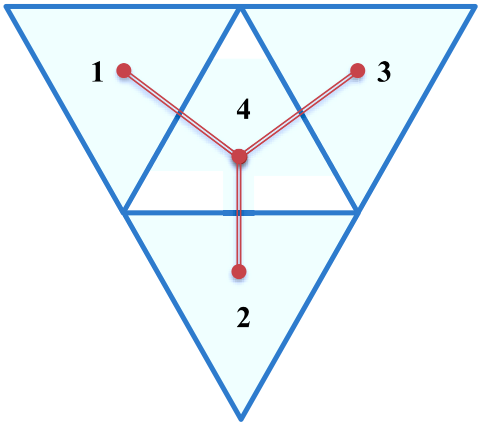


Şekil 2 Modeller Arasında Paylaşılan Parametrik Değerler

Yukarıdaki şekilde görüldüğü üzere, Ayrık Seçim Modeli, temel olarak, belirli bir bölgede çalışan ve belirli bir beceri seviyesine sahip insanların konut yeri ve ulaşım modu tercihlerine göre dağılımlarını hesaplamakta ve bu toplam değerleri hesaplanabilir genel denge modeli ve ulaşım modeli ile paylaşmaktadır. Ulaşım modeli, bu değerleri OD matris olarak kullanmakta ve ulaşım tercihlerine göre insanları, ulaşım ağındaki bağlantılara atamaktadır. Bu atama işlemi ulaşım ağındaki yoğunluğu ve dolayısıyla bölgeler arası ulaşım sürelerini ve maliyetlerini ortaya çıkarmaktadır. Bu değerler, ayrık seçimi modeli ve hesaplanabilir genel denge modeli içerisinde girdi olarak kullanılmaktadır. Hesaplanabilir genel modeli, ise ayrık seçim modeli ve ulaşım modelinden aldığı parametreleri de kullanarak ekonomideki genel fiyat düzeyleri ile hanelere göre harcama profillerini oluşturmaktadır.

SENARYO ANALİZİ

Bu Tezde, önerilen modeli farklı senaryolarda test etmek için Şekil 3'te görülen dört farklı bölgeden oluşan bir kent için yapay veri seti oluşturulmuştur.



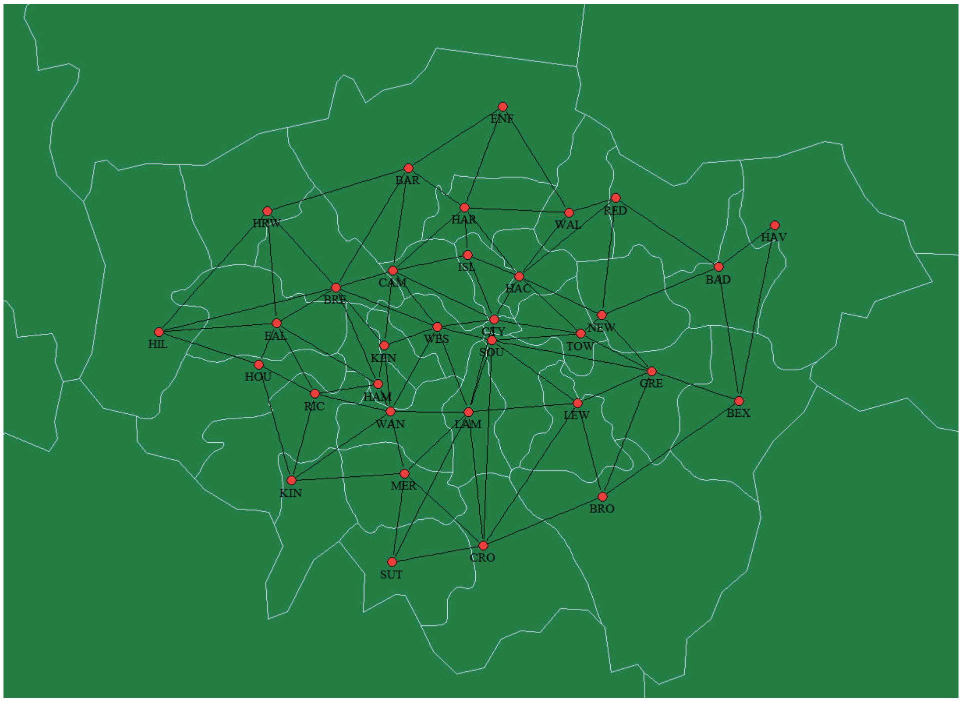
Şekil 3 Dört Bölgeli Kent Modeli

Daha sonra, bu veri seti kullanılarak, aşağıdaki senaryoların analizi yapılmıştır:

1) Özel ulaşımın kapasitesinin artırılması: 1. Bölge ve 3. Bölge arasında özel araçlara tahsisli yeni bir yol yapılması
2) Toplu taşıma kapasitesinin artırılması: 1. Bölge ve 3. Bölge arasında toplu taşıma araçlarına tahsisli yeni bir yol yapılması
3) Kent merkezine (4. Bölge) girişin ücretli hale getirilmesi

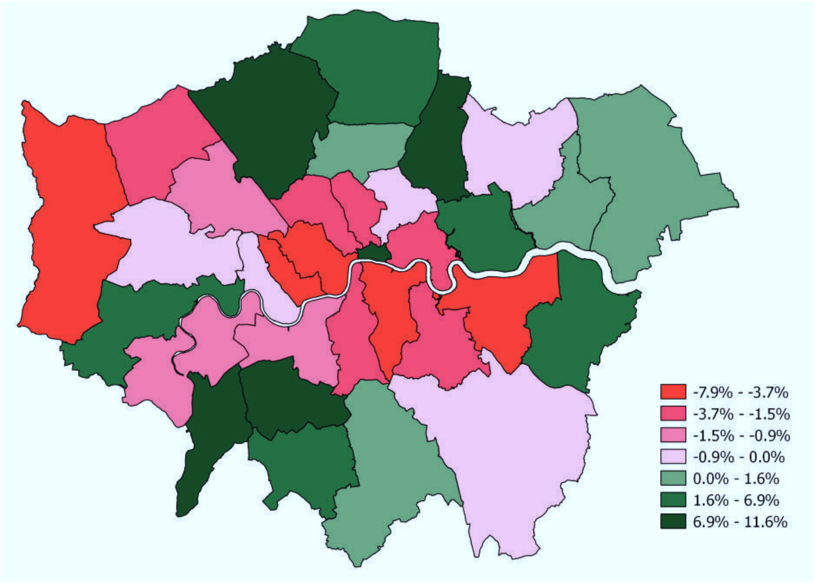
Yapılan analizler sonucunda, hanehalkları arasındaki heterojenlik (tercihler, fiyatlandırmalar, vb.) seviyesinin önemli etkenler olduğu ortaya çıkmıştır. Hanehalkları, aynı değişikliğe farklı şekilde tepki verebilmektedir. Bu nedenle, kentlerin ve kentlerde yaşayan hane halklarının ayırt edici özelliklerini irdelemek ve bunlara ilişkin parametreleri doğru bir şekilde tahmin etmek çok önemlidir. Bunlar yerine getirilmeden yapılacak analizler, doğru politikaların geliştirilmesinde yetersiz kalacaktır.

Bir başka analiz, Londra'da yapılması planlanan Crossrail 2 projesi sonrasında elde edilecek toplu taşıma erişilebilirliğindeki iyileşmenin olası etkileri için yapılmıştır. Bu analiz için, Londra'da yer alan 33 ilçeden oluşan Şekil 4'teki ulaşım ağı oluşturulmuştur. Bu ulaşım ağında, ilçelerin merkezlerinden geçen yollarla birbirlerine bağlandığı kabul edilmiştir.



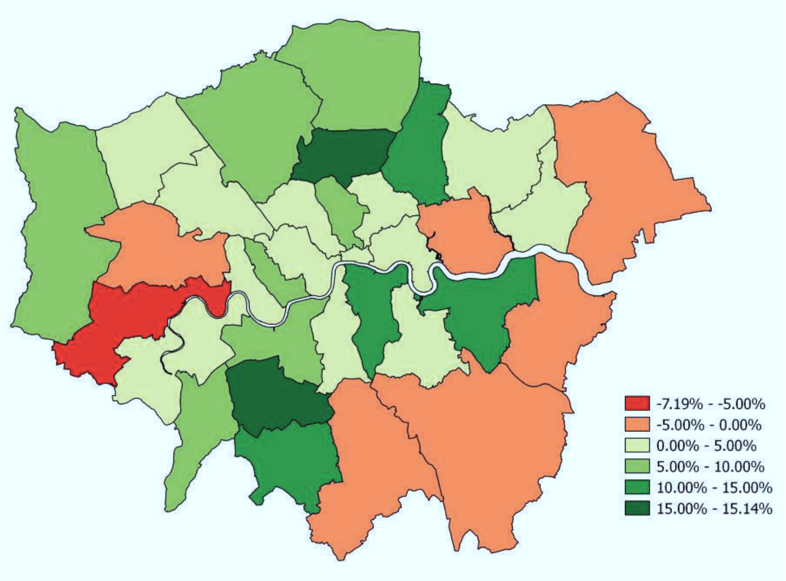
Şekil 4 Londra Ulaşım Ağı

Crossrail 2 projesi sonucunda elde edilecek erişilebilirlik artışının dört farklı alandaki etkileri incelenmiştir. Bu alanlar: (i) konut fiyatlarındaki değişim, (ii) ulaşım modal dağılımdaki değişim, (iii) hanehalklarının konumsal dağılımındaki değişim ve (iv) özel araç ulaşım süresindeki değişim.



Şekil 5 Konut Fiyatlarındaki Değişim

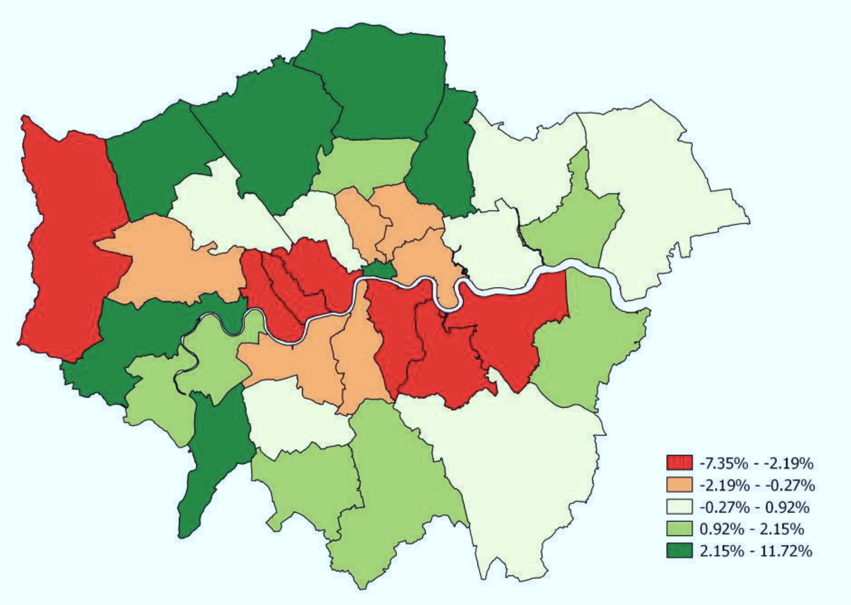
Şekil 5'te görüldüğü üzere, Crossrail 2 projesi sonucunda ulaşılacak denge noktasında, proje sonucunda erişilebilirliği en fazla artan kuzey ve güney batı Londra'da yer alan ilçelerdeki konut fiyatları önemli ölçüde artarken, kent merkezindeki konut fiyatları göreceli olarak düşmektedir. Bu fiyat değişimi, Londra'nın dış çeperlerine doğru bir talep artışı olacağına işaret etmektedir.



Şekil 6 Toplu Taşımanın Payındaki Değişim

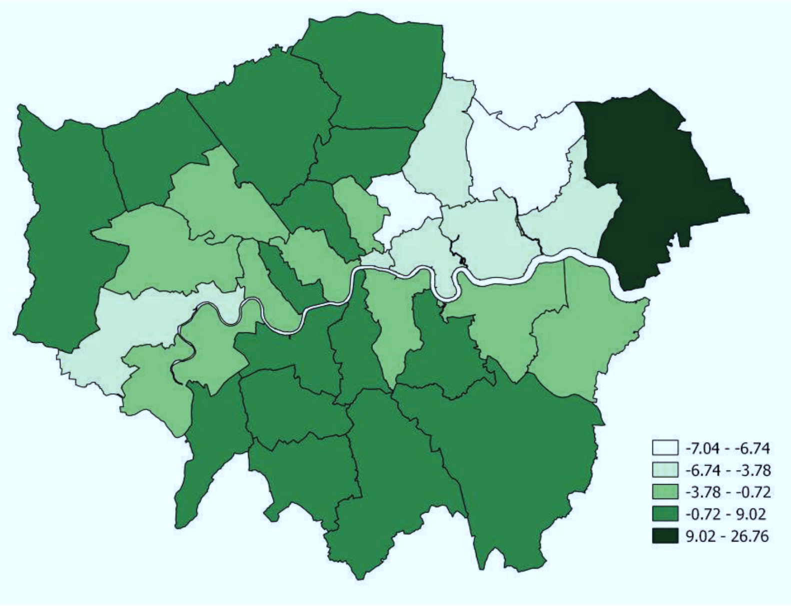
Bir başka etki alanı olan modal dağılıma bakıldığında, toplu taşımanın payının ciddi oranda arttığı görülmektedir. Kent genelinde yüzde 67 olan toplu taşıma payı, proje hayata geçirildikten sonra yüzde 71'e çıkmaktadır. Bu artışta en büyük pay sahiplerinin, yine toplu taşıma erişilebilirliğinde en fazla artış sağlanan bölgeler olduğu görülmektedir.

Hanehalklarının konumsal dağılımındaki değişime bakıldığında, en fazla nüfus kaybının kent merkezinde, en fazla nüfus artışının da Crossrail 2 projesi sonucunda erişilebilirliği en fazla artacak olan kuzey ve güney batı Londra'daki ilçelerde olacağı anlaşılmaktadır. (Şekil 7)



Şekil 7 Hanehalkı Konumsal Dağılım Değişimi

Crossrail 2 projesi sonucunda daha fazla sayıda kişi toplu taşıma kullanacak ve bu sayede de özel araçlarla yapılan yolculuklarda da belirli ölçüde iyileşme sağlanabileceği beklenmektedir. Şekil 8 böyle bir etkinin kısıtlı da olsa gerçekleşeceğini göstermektedir. Burada en fazla etkinin uzun yolculukların yapıldığı Havering ilçesinden yapılan yolculuklarda olacağı görülmektedir.



Şekil 8 Başlangıç Noktasına Göre Özel Araç Yolculuk Sürelerindeki Değişim

SONUÇ

Bu Tezde, kent ölçeğinde çalışan tam entegre bir CGE modeli kurgulanmıştır. Bu entegre modelde, üç farklı model (ekonomik model, hanehalkı seçim modeli ve ulaşım modeli) eş anlı olarak çalışabilmektedir. Bu sayede, farklı iterasyonlara gerek duymadan, denge noktasında oluşan değerler hesaplanabilmektedir.

Ayrıca, bu Tezde, trafik atama probleminin denklem setine dönüştürülmesini sağlayan yeni bir yöntem ortaya konulmuş ve entegrasyon sürecinde uygulanmıştır. Önerilen bu yeni yöntem sayesinde, trafik atama problemi entegre model yapısı içinde diğer modellerle birleştirilebilmiştir.

Tez kapsamında yapılan analizler sonucunda, hanehalkları arasındaki heterojenliğin model sonuçları üzerinde önemli etkileri olduğu görülmüştür. Bu durum, politika ya da büyük ölçekli proje geliştirirken, kentlerin demografik yapılarının çok iyi irdelenmesi gerektiğine işaret etmektedir.

Bunun yanı sıra, Londra'da yapılması planlanan Crossrail 2 projesi için yapılan analizler sonucunda, toplu taşıma erişilebilirliği üzerinde önemli etkileri olacak bu projenin, başta konut fiyatları olmak üzere bir çok alana önemli etkileri olacağı görülmüştür. Örneğin, sonuçlar, Waltham Forest ve Barnet ilçelerindeki konut fiyatlarının sırasıyla yüzde 8,9 ve yüzde 8,8 artacağını göstermektedir.

Projenin bir başka etkisi, toplu taşıma kullanımı üzerine etkisidir. Sonuçlara göre, Londra'da ev-iş arası yolculuklar için yüzde 67 olan toplu taşımanın payı yüzde 71'e çıkacaktır. Bunda en büyük pay, doğal olarak, Crossrail 2 projesi sonucunda toplu taşıma erişilebilirliğinin en fazla arttığı bölgelerde olmaktadır. Örneğin, Kingston upon Thames ilçesindeki toplu taşıma payı yüzde 23,6 oranında artmaktadır.

Bu Tez, ulaşım alanında yapılan CGE modelleri arasında 'tam entegrasyon' yönteminin kullanıldığı ilk çalışmadır. Bunun yanı sıra, bu çalışmanın literatüre yaptığı bir diğer katkı, kurgulanan modelin gerçek veriler kullanılarak yapılması planlanan bir proje için uygulanmasıdır. Bu, önemli ölçüde veri seti oluşturma çalışmaları gerektiren uzun bir süreçtir. Çünkü hanehalkı anketlerinde yer alan ayırt edici özelliklerin dikkatli bir şekilde analiz edilmesi ve bunların model içerisinde temsil edilmesi, özenli ve uzun süren bir çalışmayı gerektirmektedir.

Önerilen model, bir çok anlamda geliştirilebilecektir. Öncelikli olarak, kamu kesiminin model içerisine dahil edilmesinin önemli bir gelişme ekseni olduğu düşünülmektedir. Böylece, kamu politikalarının kamu maliyesi de dikkate alınarak daha doğru analiz edilmesi mümkün olacaktır.

Bir diğer gelişme ekseni ise, insanların çalışma üzerine verecekleri kararların modellenmesidir. Bu bağlamda, insanların çalışıp çalışmama kararı, çalışma kararı alırlarsa nerede çalışacakları gibi bir çok ayrık seçimin modellenmesi, model sonuçlarında önemli ölçüde iyileşme sağlayacağı gibi farklı analizlerin yapılmasına da imkan sağlayacaktır.

Model statik yapılı bir modeldir. Modelin dinamik hale getirilmesi de önemli bir gelişme eksenidir. Bu sayede, zamana uygulanacak politikaların zamana bağlı etkileri daha net bir şekilde ortaya konulabilecektir.

Altyapı ve alan ihtiyaçları gibi bir çok sebepten ötürü, firmaların yer değiştirme kararı alması hanehalklarının yer değiştirme kararlarına göre daha zordur. Bu açıdan bakıldığında, firmaların yer seçim kararlarının modellenmesi oldukça zordur. Bundan dolayı, bundan sonraki çalışmalarda, firmaların yer değiştirmeyeceği varsayımına bağlı kalınması tavsiye edilmektedir.

TEZ İZİN FORMU / THESIS PERMISSION FORM

ENSTİTÜ / INSTITUTE

Fen Bilimleri Enstitüsü / Graduate School of Natural and Applied Sciences ☐

Sosyal Bilimler Enstitüsü / Graduate School of Social Sciences ☐

Uygulamalı Matematik Enstitüsü / Graduate School of Applied Mathematics ☐

Enformatik Enstitüsü / Graduate School of Informatics ☐

Deniz Bilimleri Enstitüsü / Graduate School of Marine Sciences ☐

YAZARIN / AUTHOR

Soyadı / Surname : YILMAZ ....
Adı / Name : ÖZHAN..
Bölümü / Department : İKTİSAT/ECONOMICS..

TEZİN ADI / TITLE OF THE THESIS (**İngilizce** / English) : EVALUATING WIDER IMPACTS OF TRANSPORT USING AN INTEGRATED URBAN CGE MODEL ....
....

TEZİN TÜRÜ / DEGREE**:** **Yüksek Lisans** / Master ☐ **Doktora** / PhD ☐

1. **Tezin tamamı dünya çapında erişime açılacaktır. /** Release the entire work immediately for access worldwide. ☐
2. **Tez iki yıl süreyle erişime kapalı olacaktır.** / Secure the entire work for patent and/or proprietary purposes for a period of **two year**. * ☐
3. **Tez altı ay süreyle erişime kapalı olacaktır.** / Secure the entire work for period of **six months**. * ☐

***** *Enstitü Yönetim Kurulu Kararının basılı kopyası tezle birlikte kütüphaneye teslim edilecektir.*
A copy of the Decision of the Institute Administrative Committee will be delivered to the library together with the printed thesis.

Yazarın imzası / Signature .... **Tarih** / Date ....