Polycentricity and Sustainable Urban Form

An Intra-Urban Study of Accessibility, Employment and Travel Sustainability for the Strategic Planning of the London Region

Duncan Alexander Smith

Centre for Advanced Spatial Analysis & Department of Geography

University College London

A thesis submitted for the degree of Doctor of Philosophy (Ph.D.).
Revisions submitted August 2011.

Declaration of Authorship

I, Duncan Alexander Smith, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

This research thesis is an empirical investigation of how changing patterns of employment geography are affecting the transportation sustainability of the London region. Contemporary world cities are characterised by high levels of economic specialisation between intra-urban centres, an expanding regional scope, and market-led processes of development. These issues have been given relatively little attention in sustainable travel research, yet are increasingly defining urban structures, and need to be much better understood if improvements to urban transport sustainability are to be achieved. London has been argued to be the core of a polycentric urban region, and currently there is mixed evidence on the various sustainability and efficiency merits of more decentralised urban forms. The focus of this research is to develop analytical tools to investigate the links between urban economic geography and transportation sustainability; and apply these tools to the case study of the London region.

An innovative methodology for the detailed spatial analysis of urban form, employment geography and transport sustainability is developed for this research, with a series of new application of GIS and spatial data to urban studies. Firstly an intra-metropolitan scale of spatial analysis is pursued, allowing both an extensive regional scope and a sufficiently intensive local level of detail to analyse the decentralisation processes described above. Secondly a series of detailed spatial datasets are introduced to analyse employment geography and dynamics, including business survey data and fine-scale real-estate data. For the measurement of accessibility, detailed network analysis and congestion data is used. Finally for the assessment of transportation sustainability, an indicator of CO_2 emissions at intra-urban scales is developed, and is calculated for the 6.5 million journey-to-work trips in the study region. The results highlight extreme intra-urban variation in accessibility, employment geography and travel carbon emissions with clear relevance to urban form and sustainable travel debates in the London region.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I wish to thank my supervisors, Mike Batty and Andy Hudson-Smith, for their enthusiasm and guidance, and for their tireless work in creating the rich research environment of CASA. Friends and colleagues at CASA, past and present, have been inspiring and helpful, particularly Andrew and Aidan early on in the research. Finally, my parents have been incredibly supportive throughout this work, and for this I am very grateful.

Introduction

A major transformation in urban spatial structure occurred during the 20th century, with the traditional monocentric organisation of cities evolving in many cases into a variety of decentralised configurations of urban land uses. Several concepts and theories have been developed to understand these varied urban forms[1], and this research makes particular use of polycentric urban region studies (Hall and Pain, 2006). Theories of polycentric urban forms highlight the multiple diverse centres in contemporary cities: from high-density pedestrian urban cores to dispersed high-tech business and industrial parks. Secondly they relate to the increasing regional connectivity of cities, with travel patterns and business connections expanding across the region and outgrowing administrative structures. Businesses are increasingly global in outlook and integrated with international communication and transport hubs. These changes in the evolution of urban form are bound up with increasing mobility and locational flexibility for firms and residents, and increasing specialisation and polarisation of the global knowledge-based economy (Scott, 1996; Soja, 2000). The interplay of these trends has pushed and pulled urban structure, with simultaneous forces of concentration and dispersion changing economic geography and underpinning the formation of new urban forms (Hall, 1999).

This research thesis develops tools to analyse changes in urban form and economic geography, and measures how these changes are affecting travel patterns and sustainability. This involves exploring the complex relationships between economic specialisation, the built-environment and travel behaviour. The environmental impacts of transportation most directly relate to energy use and carbon emissions. These impacts result from interactions between business

---

[1] These concepts have included multi-nuclei cities (Harris & Ullman, 1945), 100 mile cities (Sudjic 1995), edge cities (Garreau 1991) and network cities (Meijers 2007) amongst others, as discussed in Chapter 1. In this research the polycentric urban region concept is the focus due to its regional scope and direct application to major world cities such as London.

and residential location behaviour, urban structure, transportation networks, and government policy. There is considerable uncertainty and mixed evidence on what the implications of more decentralised urban forms are for sustainable travel (Banister, 2005; Cervero and Wu, 1997). Polycentric urban regions have not only been identified as the emergent spatial form of global cities (Hall and Pain, 2006) but also have been proposed as a planning solution for achieving efficiency and sustainability goals (Davoudi, 2003). The focus of this research is to develop an empirical methodology to provide detailed measurements of urban form, economic geography and travel sustainability for city-regions; and then apply this methodology to the case study of London.

The urban region of London and the wider South East features a high density core, network of town centres and extensive public transport infrastructure. Thus the region appears well positioned to adapt to the requirements of sustainable urban transportation. Yet forces of specialisation and dispersion have similarly created a series of planning challenges in this region. Changes to employment and residential patterns have led to higher levels of long distance car-based commuting (Frost and Spence, 2008), with the growth of jobs beyond Greater London in the wider region. Major planning challenges include how growth can be achieved in a sustainable and efficient fashion, and how greater equality in economic opportunities can be enabled.

Research Aims

This research thesis is an empirical investigation of how changing patterns of employment geography are affecting the transportation sustainability of the London region. In answering this question we first review the research literature on changing patterns of urban form and economic geography in Chapters 1 and 2, and then consider the evidence linking transportation sustainability to urban form in Chapter 3. The literature review is followed by the development of the methodology for the empirical analysis of city-region economic geography, urban form and travel sustainability in Chapter 4. This methodology is then applied to the London region, analysing urban form and economic geography in Chapter 5 and journey-to-work sustainability in Chapter 6. Finally conclusions

on the analysis and its implications for urban research and strategic planning in London are discussed.

The overall research question of how changing patterns of employment geography are affecting the transportation sustainability is tackled through six more detailed research aims -

1. ***To identify the forces that have changed urban structure and economic geography, and that have resulted in processes of decentralisation.***

First of all we need an overview of how the socio-economic and physical structure of cities emerges, and to identify the processes that have led to changes in urban form over the 20th century. Chapter 1 reviews the evolution of urban form from the perspective of urban geographical theory. Evolving transportation and communication technologies have allowed cities to deliver high levels of accessibility through radically different dispersed physical forms in the 20th century. These changes are part of wider processes of economic change, and the economic nature of contemporary world cities, of which London is a prime example, is discussed in Section 1.2. The ideas of Chapter 1 are further extended in Chapter 2 from the complementary perspective of location theory and micro-economics. This discussion is based on how the individual behaviour of firms and residents affects macro-urban structure. A key factor in the location patterns of firms is the advantages of inter-firm proximity known as agglomeration economies, discussed in Section 2.2, which can counterbalance the dispersion forces discussed in Chapter 1.

2. ***To define urban sustainability in relation to the transportation sector, and analyse evidence on the links between urban form and transportation environmental impacts.***

In Chapter 3 we move to a normative assessment of what makes 'good' urban form from the perspective of environmental sustainability. Sustainability is frequently cited as the defining rationale of current urban planning policy, yet progress in reducing energy use and carbon emissions has in many cases been limited, particularly for the transportation sector, which has an extensive role in energy security risks and producing CO_2 emissions.

14

Section 3.3 provides a detailed review of the evidence base analysing relationships between urban structure and travel sustainability. Several scales of analysis are considered, from international city comparisons to micro-scale behaviour patterns. The need for more research at intra-metropolitan scales is advocated. Furthermore the employment dynamics and agglomeration processes that were identified as central to changing urban structure in Chapters 1 and 2 are largely overlooked in the sustainable travel literature, and analysing relationships between these economic processes and travel patterns is the key aim of this research.

3. ***To develop a methodology to analyse the urban form, employment geography, accessibility and transport sustainability of city-regions at an intra-metropolitan scale.***

The conclusions from the reviews in Chapters 1-3 feed into the spatial analysis methodology in Chapter 4 to provide indicators of urban structure and transportation sustainability at an intra-metropolitan scale. There are four categories of indicators that are developed: socio-economic, built-environment, accessibility and travel pattern indicators. As the focus of this research is on relationships between employment dynamics and travel patterns, the socio-economic and built-environment indicators are tailored to this economic geography aspect, measuring employment change, specialisation and commercial property rents (as well as density and land use measures) using business survey and real-estate data. The approach for the empirical measurement of accessibility uses transport network and speed data to accurately capture mode-specific travel times (although a full generalised cost model is not achieved here). Finally the travel pattern indicators measure the actual travel flows across a city-region, based on mode-choice and travel distance measures. These measures are synthesised into an intra-metropolitan transport CO_2 emissions indicator. Note that the demanding data requirements needed to calculate the CO_2 indicator at the intra-metropolitan scale restricts the analysis to journey-to-work travel.

*4. **To develop an empirical analysis identifying monocentric and polycentric forms, and relate this analysis to the urban structure indicators.***

Polycentricity is a scale dependent concept that is used somewhat ambiguously in the geographical and planning literature (Parr, 2004), and the spatial analysis methods used in this research provide the opportunity for a more empirically robust definition of this concept. A spatial analysis technique to differentiate between monocentric and various decentralised forms (including polycentric forms) is developed in Chapter 4 (Section 4.6) using the linked spatial measures of centralisation and concentration. The socio-economic, built-environment and accessibility indicators described in Research Aim 3 can all be analysed using this technique.

*5. **To apply the urban form and transport sustainability analysis methodology to the London region and address the following points:***
   *i) **The structure and dynamics of economic activities in the London region, and extent to which these can be considered polycentric;***
   *ii) **The transport sustainability (in journey-to-work terms) of the current structure of the London region at an intra-metropolitan scale of analysis;***
   *iii) **The relationships between economic geography and journey-to-work patterns in the study region.***

After the spatial analysis methods have been developed in Chapter 4, these are then applied to the study region of London in Chapters 5 and 6. The spatial structure and dynamics of employment, economic specialisation, and the built-environment are considered in Chapter 5, including an assessment of the degree of polycentricity in the London region's economic activities. This is followed in Chapter 6 by the analysis of accessibility and the travel sustainability of journey-to-work patterns, including travel distance, time, mode-choice and an integrated CO_2 emissions indicator. This provides a detailed evidence base to analyse journey-to-work sustainability and efficiency in the London region, and to consider how well integrated spatial patterns of living and working are. Finally the travel pattern analysis is related to the socio-economic and built-environment analysis from Chapter 5 using multivariate regression to consider

how influential employment and property market factors are in influencing journey-to-work patterns.

6. ***To discuss the implications of the research results for planning policy, and consider whether promoting greater polycentricity in spatial economic terms would bring sustainability benefits for the London region.***

Based on the findings from the above analysis of the urban structure and travel patterns in London, the conclusions to the thesis are presented in Chapter 7. Current strategic planning policies are considered in relation to the journey-to-work transport sustainability research results, asking whether a less centralised approach to future growth would be a beneficial direction for the London region. This discussion places the research in the wider context of other significant planning related factors, such as urban regeneration challenges. The insight gained from the indicators of urban structure and travel patterns developed is assessed, alongside limitations and future prospects for the methodology.

Methodology

Understanding the nature of contemporary cities creates a series of demands on the analytical tools of urban geography and planning; demands that research has arguably not fully responded to. There are four main methodological challenges in urban sustainability research that this thesis addresses: combining regional and local urban scales of analysis; integrating socio-economic and built-environment geographies; considering employment geography and market processes in urban sustainability research; and finally effectively communicating urban sustainability analysis results using composite indicators. The proposed solutions to these challenges make extensive use of Geographical Information Systems (GIS) and the associated techniques of mapping, data visualisation and spatial statistics.

In terms of scale, a comprehensive spatial conception of contemporary cities requires both a regional scope to consider the expanded regional sphere of influence of urban economies, in combination with a sufficient level of detail to

highlight intra-urban variation between populations and urban centres. Urban empirical studies are dominated by research with either a large study extent and coarse level of detail, or a more restricted study extent and detailed micro-analysis (Talen, 2003). The move towards regional urban analysis at finer spatial scales is significant in understanding urban economic and sustainability relationships. There are various data and computational challenges in achieving improved scale flexibility, and here a meso-scale urban analysis is pursued, using aggregation methods to synthesise micro-data to be applied in regional analysis.

In terms of geographical and physical integration, the socio-economic geography and built-environment structure of buildings and transportation are constantly interacting in cities and should be analysed together. Methods from geographical (spatial socio-economic) analysis and physical (built-environment and transport network) analysis can be combined in what has been termed an integrated *geographical and geometrical* approach (Batty, 2000). The introduction of micro-level built-environment and transport network data are the main innovations in this sense and this augments the geographical evidence base with detailed measures of urban form, function and accessibility. In sustainable travel research the analysis of physical planning variables in isolation from socio-economic context has been criticised (Ewing and Cervero, 2001; Gordon, 2008) and the integrated approach pursued here is intended to overcome this issue.

Further to the geographical-geometrical integration, this research also focuses on bringing a greater employment geography and property market focus to urban sustainability research. Business location patterns and market processes are important drivers in urban dynamics. Employment geography is a key component of travel patterns that has been given comparatively little attention in urban sustainability research (Banister, 2005; Ewing and Cervero, 2001), yet employment decentralisation has been central to changing travel patterns. This research uses employment, business survey and property rental data to provide evidence on the key role employment location plays in commuting behaviour.

Finally, it is necessary to translate the extensive quantitative analysis into meaningful results that can be used by researchers, planners and policy makers. This research focuses on calculating and mapping indicators of key concepts of density, accessibility, specialisation and travel sustainability. The main original contribution is the development of an intra-urban indicator of travel CO_2 emissions, allowing a clear summary of the intra-metropolitan variation in travel patterns.

Chapter 1

Accessibility, Agglomeration and the Evolution of Urban Form

This chapter reviews urban geographical theory on how the socio-economic and physical structure of cities has evolved. In particular the processes that have led to changes in urban form over the 20th century and given rise to dispersed and polycentric forms are analysed, thus addressing Research Aim 1 from the thesis introduction. The history of cities is characterised by a high degree of dynamism, in economic systems and production technologies, whilst being offset by a remarkable continuity in certain aspects of physical structure. The dynamics of cities is considered in this chapter through reviewing economic theory of capitalist 'creative destruction' cycles, and the changing modes of production and urban technologies that result from these cycles. The evolution of transportation technology is central to changing urban form and is reviewed in detail, particularly the rise of the automobile and subsequent urban dispersion in the 20th century. Despite this dynamic nature of urban growth, we argue that the central purpose of cities in facilitating accessibility has not changed from the very first urban settlements to the present day, and transport innovations have increasingly allowed intra-urban and inter-urban accessibility to be delivered far more flexibly and over far greater distances.

In Section 1.2 we examine more explicitly the economic activities in contemporary world cities, which are directly relevant to the study region of London. This section describes how processes of economic specialisation and globalisation are altering the spatial form of world cities. These processes have been argued to underpin the emergence of polycentric forms.

1.1   The Evolution of Urban Spatial Structure

This section discusses cycles of capitalism and technological innovation, and how these are linked to periods of urban growth and the physical intra-urban structure of cities. The ability of cities to facilitate contact and communication between populations is arguably the very reason for their existence, and transportation is therefore a key technology as it determines the range at which urbanisation economies can function. Innovation in urban transport networks has been central to the spectacular growth of cities the last two centuries as discussed in Sub-Sections 1.1.3 and 1.1.4. There is a tension between the forces of centralisation and dispersion in cities which is linked to the common structures of monocentric and decentralised urban forms. Finally in Sub-Section 1.1.5 we discuss how the dynamic nature of the urban economy is offset by processes of continuity or 'path dependence'.

1.1.1   The Foundation of Cities: Contact and Communication

Why live in a city? Why do business in a city? Why construct vast and complex cities as places to live and do business in? The success and arguably very purpose of cities lies in their ability to enable contact and communication by bringing large populations into close proximity. The forces of proximity are simultaneously economic, social and political in nature, and have been manifested in a rich variety of urban forms, influenced by the historical diversity of socio-economic systems and modes of urban technology (Hall, 1998a). As urbanisation has accelerated and the number of city dwellers has swollen to over half the global population at 3.3 billion (UNFPA, 2007), the forces driving urban growth are clearly more central than at any time in the organisation of global society.

The economic benefits of urban population concentration are several. Greater efficiency of production is possible through close proximity to markets, to inputs such as labour, to competition and cooperation with other businesses, and more generally to the potential for greater economies of scale (Fujita and Thisse, 1996). These benefits are collectively referred to as agglomeration economies (see Sub-Section 2.2.3). Such economic drivers have been central to

the growth and spatial structure of urban settlements throughout history, from early market based settlements that traded by water and land with agricultural hinterlands and other settlements (Jacobs, 1969); to industrial manufacturing centres with concentrations of factories, labour and rail and sea trade connections (Soja, 2000); finally to post-industrial cities where agglomerations of knowledge intensive services locate and electronic communication networks and flows of capital are central (Castells, 2000).

These various urbanisation economies require labour. Cities are centres of employment at high levels of specialisation, thus attracting populations seeking jobs and higher wages. Furthermore there are many other social attractions for urban living. Urban residents can form wider social networks, access various educational, social and leisure facilities, and to experience the 'buzz' of urban culture (Glaeser *et al.*, 2001; Storper and Venables, 2004). Cities act as social markets for finding relationship and marriage partners, and are the focus for migration, particularly of the young. In addition to these benign reasons for city growth, urban migrations have resulted from severe socio-economic change, driven by rural unemployment from agricultural modernisation, and by events such as famine. In relation to the social attractions of urban life, cities are melting pots of ideas and cultures. Urban proximity enables socio-cultural practices and knowledge to be shared and for new cultures to emerge. Cities are the great centres of news and media, cultural production, artistic expression, education science and research, fashion and trends (Hall, 1998a). Furthermore cities are also centres of political power and influence, with the nature of such networks changing greatly over time with the evolution of political systems. This began with the earliest cities where religious tribute was the means of extracting agricultural surplus from hinterland farmers (Soja, 2000) and continues to the structures of national and international governance in the present day.

In summary, cities enable contact and communication by bringing populations into close proximity. The advantages of proximity are simultaneously economic, social and political, and are connected to the culture and technology of the city and its era.

1.1.2 Cycles of Urban Growth and Capitalism

The explosive growth of cities in Europe and North America, and more recently in Newly Industrialised Countries, has occurred during various phases of capitalism[1]. There are significant linkages between eras of capitalism, technological innovations and cycles of economic (and urban) growth. The presence of long term economic cycles was advocated by Kondratieff (1935) who identified fifty-year *long waves* of growth and stagnation in the British and French industrial economies. Links between these economic cycles and technological innovations were proposed by Schumpeter (1939) in his business cycle theory of 'creative destruction', and subsequently expanded on by the evolutionary school of economics (Fagerberg, 2003; Perez, 2002). Groups of technological innovations cluster together to boost productivity, stimulating phases of economic growth and capital accumulation. This growth continues until markets are saturated and profits fall, leading to stagnation or decline, as illustrated in Figure 1.1. Further innovations are required to bring about a new phase of growth.

Perez (2002) calls these linked phases of development *techno-economic paradigms*, and argues they determine the main form and direction in which productivity growth takes place during that period, as shown in Figure 1.2. These paradigms include transportation and communication technologies, which play a key role in capitalist evolution as they diminish the spatial barriers to the movement of commodities, people and information; thus expanding markets and increasing productivity (Harvey, 2001). Note also that growth is fundamentally dependent on fossil fuel exploitation. The techno-economic paradigm viewpoint is somewhat technologically determinist, and can be criticised for downplaying the key of the state in capitalist evolution (Tickell

---

[1] Clearly capitalism is a highly complex and contested subject, but in basic terms capitalism is a socio-economic system whereby goods, capital and labour are traded in markets. The means of production are largely privately owned and are employed for private profit and accumulation (Schumpeter, 1946). In the Marxist tradition capitalism is a *mode of production* that defines the organisation and relationships between economic activities, social classes and technologies.

and Peck, 1992), and for overlooking key international structures and inequalities that define core-periphery relationships (Wallerstein, 1979). Yet despite these shortcomings, techno-economic paradigms provide a useful framework for understanding the history of urban growth.

Figure 1.1: The Life Cycle of a Technological Revolution. Source: Perez (2002).

Major Phases of Capitalism	Competitive/ laissez-faire				Disorganised/ advanced
			Organised/managerial		
Start of techno-economic paradigm	1770s in Britain	Late 1820s	Late 1870s	1910s in USA	Late 1970s
Long wave cycles and characteristics of core economies	1st Industrial Revolution Napoleonic Wars 2nd Industrial Revolution "Hungry Forties" Victorian Boom Depression of 1890s "Roaring Twenties" Great Depression Post-war boom 1970s Slump New Right Era Great Recession?				
Labour Processes	Manufacture		Machinofacture	Fordism/Taylorism	Flexible Production
Technological Systems	Early mechanisa-tion, cotton textiles, iron works, steam engines.	Coal steam engines, steel, machine tools	Electrical and heavy engineering, early combustion engine, oil and plastics, civil engineering.	Mass production, petrochemicals, aerospace industries, early electronics, high-rise construction, suburbanisation.	Microelectronics, Information Systems, Biotech, Robotics
Transportation Systems	Canals, early shipping	Railways, Steam shipping	Electric railway, metro, trams,	Automobile, aircraft	Mass automobile, mass air travel, containerisation.
Communication Systems	Post	Telegraph	Telephone	Radio and television	Digital telecom., internet
Energy Systems	Water, timber	Coal	Oil, gas, coal	Oil, gas, coal	Oil, gas, coal, nuclear

Figure 1.2: Long Waves of Economic Growth and Technology.
Adapted from Perez (2002) and Knox et al. (2003).

We can explore how economic cycles are linked to urban growth and decline by analysing population dynamics (Batty, 2007b). Cities rise to prominence in particular economic eras with rapid growth, eventually tailing off as economic downturns arrive or size limits are reached. As modes of production and profitability shift, cities can adapt to ride a new wave of growth or alternatively lose out to rival cities and stagnate. An example of city population dynamics is shown in Figure 1.3 for a selection of the largest US cities between 1850 and 1990[1].
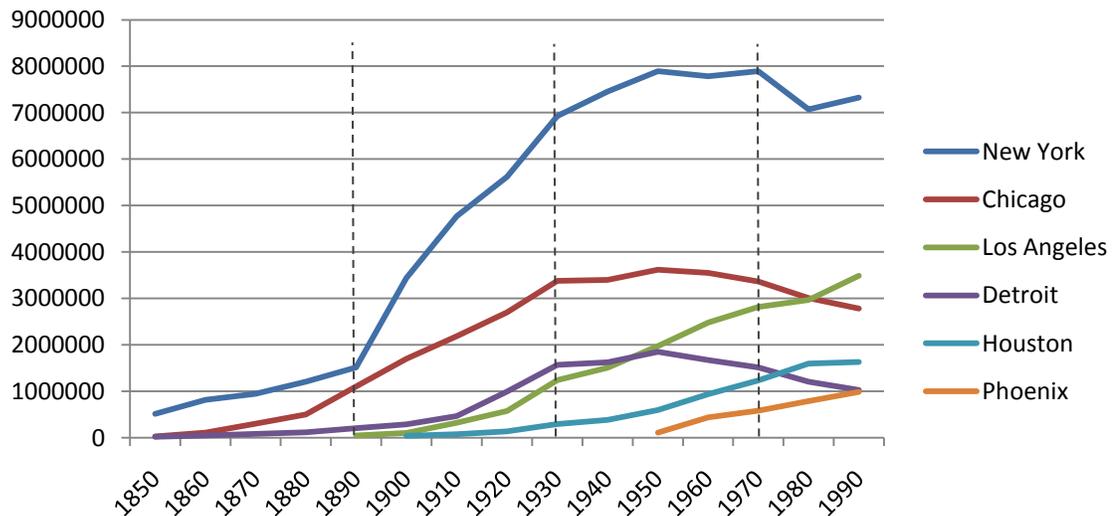
Figure 1.3: Population of Selected US City Municipalities. Source: US Census Bureau.

As can be seen US urban growth has been dramatic, particularly in the 20th century when the USA established itself as the world's leading economic power. The older industrial cities of New York and Chicago grew significantly in the 19th century. Rapid growth occurs in the early 20th century, with the cities of Detroit and Los Angeles also emerging. The rate of population growth is checked by the Great Depression, and the Fordist industrial cities of Chicago

---

[1] The dataset is not entirely accurate as it measures populations within municipal boundaries, and therefore misses out the significant trend of suburban growth beyond city boundaries. Nevertheless the data does highlight mixed economic fortunes of US cities related to economic cycles.

and Detroit stall and then decline. Meanwhile the Sunbelt cities of Los Angeles, Houston and Phoenix grew rapidly. The next economic crisis in the 1970's exacerbates this divergent growth pattern.

In summary, techno-economic paradigms are a useful framework for positioning eras of capitalism and considering relationships between the growth of cities and evolution of technology in core economies. These paradigms are strongly linked to urban spatial structure, as discussed below.

1.1.3   Transportation Systems Development and the Monocentric City

We argued above that contact and communication is central to the very existence and functioning of cities, as it underpins the attraction of urban locations to residents and businesses. It follows therefore that transportation is a critical technology as it determines the speed and range at which people and goods can be moved and where urbanisation economies can function. Innovation in transportation has been absolutely central to urban expansion. Transportation facilitates accessibility, i.e. the costs for residents and businesses to interact with other residents and businesses, and this plays a key role in urban structure.

The evolution of urban form can be viewed through the tension between forces of centralisation and forces of dispersion, with accessibility relevant to both of these forces. Pre-industrial cities were based on a compact high-density core combining commercial, residential and political functions, and maximising accessibility for non-motorised transport. The accessibility advantages of a high density central core are inevitably offset by costs, in terms of congestion, lack of space (and therefore high rent), and pollution. Transportation innovations during the industrial revolution increased accessibility at the urban periphery, allowing cities to expand and some residents to leave the congested core. Cities during this era did however retain their core commercial centre, i.e. a monocentric form, as access to labour and to inter-city import/export trade remained highest in the traditional centre. A major revolution in transportation technology would be required for centrifugal trends to outweigh monocentric structures for the majority of business activities, as discussed in Sub-Section

1.1.4. The various eras of transportation technology are connected to phases of urban growth within cities[1], as illustrated for an example US industrial city in Figure 1.4. Alongside is a map of the historical growth of Chicago which largely follows these trends (albeit with greater complexity in sub-centre formation).
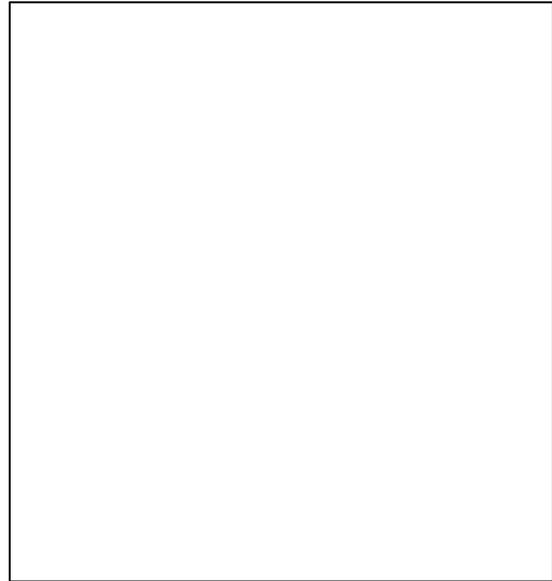
Figure 1.4: Intraurban Transport Eras and Urban Growth. Source: Adams (1970).

Figure 1.5: The Expansion of Chicago. Source: Berry et al. (1976).

Similar phases of transportation technology have affected cities across the developed world. In pre-industrial cities, transport was limited to organic means, which restricted local travel to human and animal powered modes. This constrained the range of urbanisation economies to relatively small high density settlements. Inter-city trade was mainly water-borne, which encouraged settlements to grow by navigable waterways (Hugill, 1993), such as Lake Michigan in the Chicago example. The core intra-urban transport network was the street network, allowing the movement of pedestrians and goods vehicles,

---

[1] Note there are close parallels between transport-era led growth theories and the urban morphology concepts such as burgess cycles (Conzen 1960) where cities expand in phases of concentric development from the historic core.

providing access to buildings, and defining public and private space. Street systems are themselves urban transport innovations that had to be created and refined[1], and remain of central importance in contemporary cities. Following pre-industrial eras, an array of mechanised transport innovations enabled urbanisation economies to act over far greater distances and facilitated widespread urban expansion. The first wave occurred in Britain, based around iron and cotton textiles, with canals and turnpike roads for transportation (Pollard, 1981). Urbanisation accelerated further with the second wave of industrialisation based on coal powered steam engines, spreading to mainland Europe and the USA. Access to raw materials such as coal and to labour underpinned the spatial structure of industry (Weber, 1909) leading to the emergence of the traditional industrial regions of the UK and north-east USA. Railway stations became the focal point of urban commercial growth, attracting factories, offices and housing to locate nearby in the crowded and polluted city centre (Anas *et al.*, 1998).

The desire of city residents to escape the overcrowded and polluted surroundings of the urban core stimulated intra-urban transport (Muller, 2004). Early horse-drawn transport services such as Hackney Carriages and omnibuses (Turvey, 2005) gave way to higher speed electrified tram and streetcar technologies. In London much suburbanisation was closely connected to the development of the underground rail network and commuter lines (discussed in Chapter 5). Such expansion was radial, maintaining the dominance of the city centre, with many similarities to the radial Figure 1.5 Chicago example.

From a sustainability perspective it is important to emphasise the central link between transportation costs and energy costs. Energy production also fits within the techno-economic paradigm framework, with coal power giving way

---

[1] Ancient examples of 'streetless' settlements have been uncovered, such as Catal Huyuk in Anatolia where buildings were crammed together on all sides, with access provided by climbing across roofs (Mellart 1967).

to electrical (indirect fossil-fuel) and petroleum based energy systems. The costs of fuel have fallen massively in real terms throughout the 20th century (except during major conflicts and the 1970's oil crises) based on technological innovation and economic expansion enabling unprecedented fossil fuel exploitation.

In summary, urban form is closely tied to phases of innovation and growth in transportation technology and infrastructure networks. Transportation accessibility and energy costs determine the range at which inter-city agglomeration economies can function, and are also form the basis of inter-city trade and production networks. There is a tension between centripetal and centrifugal locational forces in cities, with the urban core traditionally providing the highest accessibility to labour, customers and intra-urban rail connections, whilst being unattractive due to high costs and congestion.

1.1.4   Decentralised urban forms and the rise of the automobile

The emergence of decentralised urban forms is closely tied to economic change and the rise of the automobile in the twentieth century. The industrial production system of Fordism brought consumer goods to the mass market through greater production efficiency (and thus cheaper prices), economic growth, an expanded middle class and an oil production boom (Lash and Urry, 1987). Car ownership began to rise dramatically, and a new era of urban expansion arrived, at a pace and scale far greater than any previously experienced. This process began to invert the monocentric accessibility pattern of the traditional industrial city.

In the expanding suburbs where car ownership rose quickly, suburb-to-suburb travel became increasingly quick and straightforward, in contrast to the poor orbital accessibility offered by radial public transport networks. Inter-city accessibility also rose at the urban fringe with freeway and motorway networks beginning widespread construction in the 1950's. Previously isolated fringe locations had greatly improved accessibility, cheap rents and space for expansion. The rise of the automobile was enthusiastically supported by urban planning and government policy in the developed world through the post-war

modernist agenda. There was significant investment in road infrastructure, and a new wave of car-based suburban expansion was pursued.

The widespread adoption of private cars also had knock on effects on accessibility in the city centre. City centre streets are generally congested (especially in historic centres with narrow street layouts) and this was exacerbated by greater use of private cars due to their relative space inefficiency. In some contexts the upgrading of automobile infrastructure was combined with a downgrading of public transport infrastructure. Tram/streetcar networks closed in many UK and North American cities as road space was prioritised for private car use. The switch to the automobile led to a decline in public transport patronage on many routes, and subsequently less money for investment and in many cases service closure (Pucher, 2003).

With increasing city centre congestion and expanding connectivity and available space at the city outskirts, the balance of comparative locational advantage for businesses began to switch towards the urban fringe. The earliest identification of a decentralised city is attributed to Harris and Ullman (1945, Figure 1.6). Their multi-nuclei model theorised a US industrial city with multiple centres. The creation of these centres was related to agglomeration economies and large space requirements of Fordist manufacturing industries (which encouraged decentralisation), and negative externalities from heavy industry towards affluent residential areas. The central business district remains the largest centre in the Harris and Ullman model.

Figure 1.6: The Multi-Nuclei Model. Source: Harris and Ullman (1945).

Early decentralisation trends led to more profound structural change as the 20th century continued. Larger commercial centres emerged at the urban periphery, with new forms such as business parks and out-of-town shopping centres. These processes have been most apparent in North America, where in several cities the proportion of employment in central business districts has fallen below 10%. Such trends can also be observed to lesser degrees throughout the developed world. In addition to multi-nuclei cities, these new urban forms have been variously termed polycentric cities (Gordon *et al.*, 1989), 100 mile cities (Sudjic, 1995), and edge cities (Garreau, 1991). The terms polycentric and multi-nuclei cities are largely synonymous, whilst the term edge cities has different connotations discussed below. The 100 mile cities concept is closer to research into megacity and megalopolis phenomena describing areas such as the eastern seaboard of the USA and the Pearl River Delta in China, where growth has been so dramatic as to link previously distinct cities into massive continuous urban regions.

The term edge cities describes the process whereby new commercial centres were created in post WWII USA at the urban fringe, typically near major highway intersections (Garreau, 1991). These were not industrial centres, but large scale commercial centres with major office and retail functions. In Garreau's definition an edge city must have at least 5 million square feet (460,000 square metres) of office space and 0.6 million square feet (55,700 square metres) of retail space, thus it must be a major employment destination rather than a residential led development. Garreau identified nearly 200 such centres in the USA in 1991. Spatially these centres contrast strongly with urban cores, as they are relatively low density, functionally segregated and are entirely dependent on the car, featuring large car-parks and arterial roads that are hostile to pedestrian travel. Garreau's work was provocative in promoting edge cities as successful and efficient, and as a model of future urban form (Garreau, 1991). He provided little concrete evidence for these efficiency claims however beyond the popularity of these centres with many businesses, and his work predates current sustainability concerns.

In summary, the 20th century has seen traditional accessibility patterns increasingly inverted and the balance of locational advantages for commercial and industrial activities has shifted from the city centre towards the urban fringe. These changes towards decentralised forms represent the most dramatic change in intra-urban structure since the industrial revolution.

1.1.5   Urban Archetypes, Network Logics and Path Dependence

The previous evolutionary discussion has implied that urban growth has been a continuous process towards decentralised cities. Of course the reality is more complex in terms of the historical continuity of urban spatial structure, and the diversity of how particular cities and regions have developed. This discussion focuses on two particular concepts related to how cities resist dramatic physical change. These linked concepts are transport network logics and path dependence.

In the study of urban geography it is a truism that 'history matters'- that continuity and persistence are key characteristics of urban development (Batty, 2001b). A city that rose to prominence in the 18th or 19th centuries will be significantly different in its contemporary form to a city where the majority of growth occurred in the mid-twentieth century. Such a phenomenon has been termed *path dependence* (Arthur *et al.*, 1987), where a path dependent system is one in which the initial conditions play a key role in determining future structure. It is important to understand why such continuity is found in urban systems, particularly when urban economies are dynamic and constantly transforming[1]. Urban path dependence is related to several characteristics of

---

[1] Note that we refer mainly to the path dependence in terms of urban physical structure. Urban function is generally more dynamic, shifting with changing economic systems. Contemporary cities are full of examples of buildings transformed from their original function, from centrally located residential districts used as offices, to inner-city warehouses converted to studio flats. On the other hand, there are also many examples of continuity in function too, particularly at the urban core of monocentric cities.

urban systems, including the durable fixed-capital nature of the built infrastructure; and socio-cultural factors relating to urban practices and identity.

Buildings and transport infrastructure generally exist for the long term. They are significant capital investments in terms of materials and construction, and their durability means that value is retained over time. Typically it is cheaper to reuse and renovate than to rebuild. The value of property is both in the physical building and in the value of the location and urban area. Value becomes highly interdependent between properties, with urban streets and districts becoming massive collective investments of capital. The urban street network itself is argued to be the most consistent urban feature across time (Conzen, 1960), and certainly London confirms this view with the routes of many medieval roads and even some Roman roads remaining to the present day. That is not to say large scale physical urban reconstruction is impossible (examples exist from Haussmann's Paris to British post-war urban development) but is expensive and requires significant political willpower. Resistance to change is also bound up in socio-cultural and political processes. Cities are living environments, with collective civic identity attached to the built-environment and public space, from major symbolic civic spaces, to local residential communities. Thus social capital can also resist changes in spatial structure.

Urban transportation networks are closely connected to these processes of path dependence. This is due to the infrastructure costs of the transportation networks themselves, and to the central link between transportation, the built-environment and the functioning of cities. Furthermore different transportation modes are not necessarily compatible with each other; they display different *network logics* in the accessibility they provide and the complementary built-environment forms they encourage. Dimensions of various motorised transport modes, such as speed, capacity and flexibility, are summarised in very basic form in Table 1.1. Rail transport can carry very high densities of passengers at high speeds, whilst being inflexible, and focussed around major hubs, as well as requiring large initial capital outlays for development. Private automobile transport can also provide high speed travel, but contrasts with rail in having much greater flexibility and carrying lower capacities of passengers. The total

costs of private transport are similar to public transport (and often higher when environmental factors are considered), yet the initial infrastructure costs for conventional roads are lower, as the costs of purchasing and running vehicles are paid for by car owners. High speed restricted access road networks (i.e. motorways) on the other hand are similar to rail networks in requiring very large capital outlays.

Table 1.1: Characteristics of Motorised Transport Modes.
Source: World Bank Reports, cited in Tolley and Turton, (1995).

Mode of transport	Maximum Capacity (persons per hour)	Average speed (km per hour)	Interval between access points (km)
Urban Railways	50000-60000	32-48	1.6
Light Rapid Transport System	40000	26-38	0.5-1.3
Bus on conventional road network	9000-10000	16-24	0.2-0.5
Bus using reserved lane on express highways	20000	56	0.8-1.6
Private car on conventional road*	1000	19-40	-
Private car on urban motorway network*	3000	72-80	-

*Assuming vehicle occupancy of 1.5.

As a result of these various transport mode characteristics, the dominance of a particular transport system encourages complementary built-environment development, pulling urban development towards certain spatial structures. Thomson (1977) proposed *urban archetypes* that fully embrace the complementary spatial structure for particular transport modes. For rail dominated cities, radial structures are very common as these link all sections of a city together whilst minimising investment in expensive rail infrastructure (Figure 1.7.i). This is the monocentric form, providing high accessibility to and from the city centre, whilst orbital accessibility is poor. This limits the competitiveness of sub-centres as commercial locations. Radial networks are closely tied to the form of monocentric cities with a single commercial core. In complete contrast to the monocentric archetype, the full motorisation archetype has a very high degree of mobility and flexibility in travel patterns, with high accessibility across the entire city. The flexibility and low capacity (with resultant congestion) of private transport discourages a single dominant centre and promotes a low density dispersed pattern served by a continuous road

network grid. Travel patterns occur from multiple origins to multiple destinations using multiple routes, i.e. a complete contrast to the constrained radial journeys in the strong centre archetype. This structure is effectively modular and can expand more easily than the monocentric archetype. Road infrastructure and land costs are high, and congestion is likely to persist due to the high spatial inefficiency of the automobile.

Figure 1.7: Urban Transport Archetypes. Source: Thomson (1977).

Cities are of course in reality hybrids of these archetypes. Even highly automobile orientated cities such as Los Angeles have a downtown, whilst public transport orientated European capitals such as Paris and London have car-dominated peripheries. Nevertheless the periods in which these cities experienced their most rapid growth remain highly influential on their current structure, and attempts to develop cities serving as both public transport and private car archetypes are expensive and face significant hurdles in overcoming legacies in urban spatial structure.

1.1.6   Summary

The economic and social success of cities depends on their ability to enable contact and communication, and transportation is therefore a key technology for cities to function. Cycles in the development of capitalism have produced techno-economic paradigms that define urban functions and transportation technologies in different eras. There are close links between the types of accessibility that particular transport modes provide and urban form. A critical

change has occurred between the industrial public transport era that is associated with monocentric structures, and the decentralised forms enabled by the speed and flexibility of the automobile.

There is a critical tension between the dynamism of urban economies and the continuity of urban structure through the phenomenon of path dependence. Harvey (2001) expresses this tension between the dynamics of capital, constantly seeking new markets and technological change to increase profits, and the fixed infrastructure of capitalism (of which cities are the prime example) which are essential for capitalism to function. The continuity of urban spatial structure depends on the ability of cities to be flexible and adapt to new economic phases of capitalism, and to associated urban cultures and lifestyles.

1.2   The Form of Contemporary World Cities

The section considers the most recent phase of advanced capitalism and globalisation, and discusses the implications for the spatial structure of world cities. This current era of world city networks is central to London's recent growth and socio-economic change.

1.2.1   Globalisation and the Knowledge Economy

We now turn to a discussion of the current era of advanced capitalism. London's spectacular growth in recent decades is embedded in processes of globalisation (as conversely are the economic problems of the current financial crises). It is therefore necessary to review research into contemporary economic geography and globalisation processes. A number of complex and interrelated trends occurred in the latter decades of the 20th century that brought about changes to the dominant mode of production and to the structures of cities and their interrelationships. So-called advanced or disorganised capitalism has been characterised by accelerated internationalisation of economic processes; an integrated and volatile international financial system; new kinds of production using information technologies; different modes of state intervention; and the increasing importance of culture in production and consumption (Thrift, 2002). These globalisation processes are connected to many economic changes such as the increasingly knowledge-intensive economy, more powerful transnational corporations, deindustrialisation of core economies, and the growth of Newly Industrialised Countries (NICs) mainly in Asia and Latin America. Economic connections have become more globalised, coordinating city functions in international networks and supporting more intensive global specialisations and divisions of labour.

A major new phase of globalisation was triggered after World War II where previously closed-off imperial markets were liberalised, and the USA led the spread of Fordist production methods to Europe and Japan. Fordism is characterised by mass production and mass consumption with a greater government role in macroeconomic management and the welfare state (Lash and Urry, 1987). After two decades of dramatic growth, the profitability of

Fordist industries in core economies went into decline in the 1970's. Markets for standardised goods became saturated, the creation of floating currencies (following the collapse of the Bretton Woods system) exposed core economies to cheaper imports, and costs rose from welfare provision and political instability (Hamilton, 1984). A response of corporations in core economies has been to become increasingly transnational and shift production to NICs, taking advantage of cheaper costs and new markets. This has been facilitated by dramatic falls in transportation and communication costs, with the containerisation of shipping, cheaper air travel, and digital network innovations. Increasingly production functions have been separated from high level management and R&D activities, which largely remain in core economies (although NICs such as China and India will likely themselves become core economies in the future). Another trend in boosting profitability has been to de-standardise products and increase turn-around through more flexible production and sophisticated marketing, enabling the serving of specialised consumption markets (Scott, 1996).

While traditional manufacturing has declined dramatically in core economies, value has increasingly shifted to informational activities involved in knowledge creation and information processing (Castells, 2000). This includes high-tech sectors, such as computer software and biotechnology, and business and financial services. Financial services had previously been an ancillary activity linked to manufacturing and other services, but speculative trading and new capital markets grew massively from the 1980's onwards. The growth of financial services in key global centres resulted from a number of trends including floating exchange rates, the deregulation of financial markets, digital telecommunication technology and new markets in debt and savings (Wharf, 1995). Business service employment more generally expanded rapidly in the 1980s and has continued to grow in the last two decades (Wood, 2002). Larger more complex transnational firms have developed increasingly specialised business service requirements, in such areas as financial, management, legal, and marketing services. Rather than providing these specialised services 'in-house', there are economic efficiency advantages in meeting these demands through specialist business service companies. So-called producer services

provide intermediate inputs for the production of goods or of other services; they enhance the efficiency of operation and the value of output at various stages of the production process (Coffey and Bailly, 1992). In addition to business services other knowledge based service sectors that have expanded, including creative services and tourism, and have synergies with producer service growth (Hall, 1999).

Paradoxically whilst many business activities are increasingly footloose in their spatial location, knowledge economy activities often rely on face-to-face contact, whether for business services meeting the senior management of clients, financial services gathering the latest market intelligence, or creative services sharing ideas and live performance. This requirement for face-to-face interaction creates powerful agglomeration forces that favour the largest and best connected metropolitan centres. In combination with manufacturing trends a new global hierarchy of cities and division of labour has emerged. Financial and business service agglomerations are strongest in the highest order global cities, principally New York, London and Tokyo (Sassen, 1991), where multinational headquarters are located and can closely interact with producer services. Typologies of world city rankings have been devised based on indicators related to these activities, such as corporate headquarter locations, producer service activities and financial transactions (Beaverstock *et al.*, 1999). An example of such a typology is shown in Table 1.2. In addition to the importance of financial and business services, cities can enhance their world city status through specialisation in other information economy sectors, such as Los Angeles for motion pictures; San Francisco for information technology; Tokyo for electronics; and Milan for fashion and design. Manufacturing related activities generally take place outside of the core city itself, in linked edge cities such as Silicon Valley and Tokyo Kanagawa. It is the city and its region together that through processes of competition and cooperation create business clusters and achieve global competitiveness (Porter, 2000).

Table 1.2: Inventory of world cities. Source: Beaverstock *et al.* (1999).

Alpha world cities 1st	Alpha world cities 2nd	Beta world cities	Gamma world cities
London Paris New York Tokyo	Chicago Frankfurt Hong Kong Los Angeles Milan Singapore	San Francisco Sydney Toronto Zurich Brussels Madrid Mexico City Sao Paulo Moscow Seoul	Amsterdam, Boston, Caracas, Dallas, Dusseldorf, Geneva, Houston, Jakarta, Johannesburg, Melbourne, Osaka, Prague, Santiago, Taipei, Washington DC, Bangkok, Beijing, Rome, Stockholm, Warsaw, Atlanta, Barcelona, Berlin, Buenos Aires, Budapest, Copenhagen, Hamburg, Istanbul, Kuala Lumpur, Manila, Miami, Minneapolis, Montreal, Munich, Shanghai

Note: The typology is based on the activities of producer service firms in banking, law, accountancy and advertising. Alpha 1st cities are global centres in all these sectors, whilst Alpha 2nd are global centres in at least two of these sectors. As Beaverstock *et al.* (1999) describe, there is general agreement on the cities at the top levels, whilst different classification methods produce varying results for the lower groups. Furthermore these inventories are dynamic and more recent classifications would likely reveal changes, principally with the rising significance of cities in South East Asia.

The other side of the coin in globalisation processes is greater polarisation and inequality at several spatial scales, from the polarisation of labour within global cities, to unequal growth in national and international urban systems. Within cities there has been a growth in low value jobs in consumer services, whilst skilled blue collar jobs have declined. These groups of low pay workers contrast sharply with high earners in knowledge economy sectors. At national scales the largest metropolitan centres are disproportionately gaining in high level management and knowledge economy activities in various sectors, including in the UK (Wood, 2002), while the management proportion in smaller centres is declining as their role focuses on back office and routine production functions (Duranton and Puga, 2001).

In summary the latest phase of capitalism has seen increasing globalisation and the shifting of economic value to knowledge economy sectors such as financial and business services, the creative sector, and high technology production. Lower value manufacturing has increasingly moved to developing countries, partly through transnational corporations. These trends have established an increasingly global hierarchical network of cities with specialised functions. London occupies a key position at the highest level of this global network.

1.2.2   The Spatial Structure of Contemporary World Cities

From the previous discussion we can identify key trends in the current global economic system that have had corresponding impacts on the functional and built-environment spatial structure of world cities. These include the increasing importance of knowledge economy sectors, particularly producer services and financial services, as well as creative industries and tourism, and IT and hi-tech industries. As business connections are increasingly global the importance of global transport hubs has increased. Finally the polarisation of labour markets is connected to continued social classes divisions and housing market segregation. The following discussion is concerned particularly with spatial patterns in the highest order world cities, such as New York, Paris, Tokyo and London.

While decentralisation has been the dominant trend in urban form for the second half of the twentieth century, the growth of the post-industrial service economy has been a counterbalance to decentralisation, particularly in the highest order global cities. Business and financial services such as banking, insurance, legal and advertising sectors depend on the production and sharing of information, and intensive face-to-face interaction (Storper and Venables, 2004), as do other expanding service sectors, such as creative industries, retail, leisure and tourism activities. The location that best facilitates the knowledge sharing and face-to-face interaction of the knowledge economy remains in most cases the traditional city centre. These activities benefit from the high concentration of businesses and the central mix-of-uses that facilitates urbanisation economies. Unlike industrial activities, services have few negative externalities and more modest space demands, thus are highly amenable to city centre environments. The international skilled workforce at the centre of these services is attracted to the 'buzz' of city centre life (*ibid.* 2004).

The rapid growth of producer services has led to significant built-environment change in the city centres of high order world cities such as Paris and London. Intensification has taken place with higher density office developments, and expansion into the inner-city. Centrally located industrial areas and housing districts have been gentrified to cater for workers in the expanding information economy sectors (Atkinson, 2004). This central expansion has been curtailed

somewhat by transport capacity limits and demands to preserve the character of historic districts. The unmet demand for central office space has prompted the development of tertiary centres (Hall, 1999), which are high density office complexes developed at inner-city locations and tailored to the requirements of multinational headquarters and business services. Examples include La Defense in Paris, Canary Wharf in London and Amsterdam Zuid.

Legend
- ● City Centre
- ● Expanding central fringe
- ● Tertiary centres
- ○ Traditional town centres
- ● Business/Indust. parks
- ● Inner-city
- ○ Suburbs
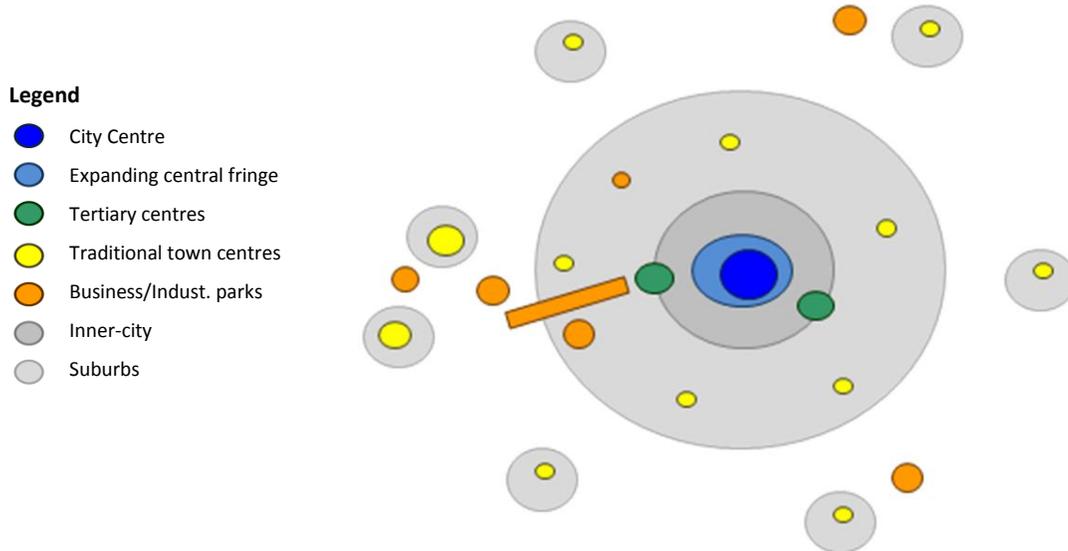
Figure 1.8: Conceptual Illustration of a Contemporary World City Region. Based on typology from Hall (1999).

Meanwhile beyond the inner-city, a wide diversity of trends in economic centres can be observed. Car-based edge cities have grown in the form of office, retail and industrial parks, typically located at highway intersections. Activities here range from distribution and logistics, to specialised services and high-tech industry. There is a strong case for aligning new forms of industrial production in the late 20th century with decentralised urban structures (Scott, 1988). Locations for hi-tech industries such as electronics, software engineering and biotechnology commonly locate in urban fringe business complexes (Castells and Hall, 1994). In addition to the cost pressures for manufacturing businesses with large space demands to locate outside of city centres, arguably the flexibility of such locations is advantageous for innovative centres, as well as providing strong access to skilled suburban workforces and access to transport facilities such as motorways and airports. The rise in air transport is a major

trend that has increased urban decentralisation. As increasing volumes of business travellers, tourists and goods flow through airports, these have expanded into massive employment, commercial and industrial hubs. Airports act as anchor points for attracting edge city growth, with related business parks, hotels and industrial growth.

Where planning policy has curtailed more dispersed growth, as in Western Europe, decentralised growth has been directed towards existing centres (Hall and Pain, 2006). This has led to the growth of existing towns and settlements around the urban fringe. Such centres have attracted back-office activities, where cheaper labour and rents can be found compared to the city centre. Retail activities and public services have also been successful in these edge-of-town population centres. It is important to emphasise that both city centre and urban fringe growth result from globalisation and specialisation processes and are to a degree interdependent. Central producer service growth is connected to urban fringe back office development, and to the growth of international travel that boosts airport edge cities. Higher city centre rents also encourage decentralisation. It is this interdependence between multiple specialised activity centres that underpins the polycentric characterisation of contemporary global cities.

In summary, the spatial pattern of economic activities in contemporary world cities involves multiple centres of specialised and interrelated economic functions. The city centre has advantages for many knowledge intensive businesses in producer service, financial and creative industries. Outer town centres, strip developments and edge-cities have comparative locational advantages in sectors such as high-technology services, manufacturing, logistics, back-office functions and large scale retail.

1.3 Chapter Conclusions

We began the chapter by asking the question from Research Aim 1- what are the processes that underlie urban spatial structure, and have given rise to decentralised forms that emerged in the 20th century? The answer from our urban geographical review is that delivering accessibility between residents and firms is the core purpose of cities, to allow urban society to function and enable economic production. The dynamics of capitalism and technology leads to constant economic and technological change, with new spatial structures emerging to facilitate new forms of production. The evolution of transportation technology has been central in determining urban accessibility and influencing spatial forms, with the revolutionary speed and flexibility of the automobile inverting the traditional monocentric pattern of accessibility in many cities. Accessibility advantages have shifted from the congested core towards the urban fringe and facilitated widespread decentralisation in economic activities.

Decentralisation trends are not the whole picture however, as these have been offset by the growth of knowledge economy industries in world cities such as London, which benefit greatly from agglomeration economies in high density clusters. This tension between centripetal and centrifugal urban economic forces is argued to underpin the formation of polycentric city regions which exhibit both decentralisation from the tradition core, and clustering in multiple specialised centres. The city centre is competitive for some economic functions whilst outer town centres, strip developments and edge cities have comparative locational advantages in other sectors such as high-tech services and back-office activities.

Looking ahead to the implications for the rest of the thesis, the changes in urban form highlighted in this Chapter will have profound impacts on the travel patterns and sustainability of cities. We can identify what factors need to be analysed when considering the degree to which a city is decentralising, and the dynamics of how urban structure is changing. Accessibility is clearly central to urban spatial change, and accessibility needs to be analysed empirically. Ideally measures need to be at regional scales to test the predictions from urban theory that regional interactions are becoming more intensive. Accessibility must also

be disaggregated by transport mode to consider how centripetal and centrifugal forces compare in particular urban contexts. Further to the importance of intra-urban accessibility, the review has highlighted how the changing nature of national and international transport hubs has important links to urban structure, thus connections between urban form and the motorway network, airports and national railway networks need to be analysed. This also requires a regional scale of analysis. On the subject of economic geography, the dynamics of employment activities in terms of the centralisation or decentralisation of jobs should provide a key indication of how firms are responding to changing accessibility patterns (as well as other important factors such as the property market and agglomeration economies, discussed in Chapter 2). This analysis also needs to consider the types of economic activities locating in particular centres, as urban theory highlights the specialised functional nature of centres and their varied locational advantages. The activities of specialist knowledge economy sectors are particularly important, as these are high value and are driving future growth in cities such as London, thus are likely to be indicative of how urban form is evolving.

Chapter 2

Urban Systems and Location Theory

In this chapter we continue on the topic of examining the forces that determine urban structure, but switch from a historical evolutionary perspective to a more functional systems dynamics perspective on cities. The discussion is centred on land use transport interaction and urban location theory. As with Chapter 1, the review addresses Research Aim 1 of explaining how decentralised urban forms have emerged. This time the focus is on the tools of systems dynamics which allow the detailed mapping of relationships between land use and travel patterns and the behaviour of urban actors. This provides a means of conceptualising the complex nature of urban processes operating at multiple spatial and temporal scales. The systems approach is complementary to the perspective that socio-economic activities, physical structure and travel patterns all closely linked and interacting in cities. This is a critical point when trying to understand urban relationships and to measure these factors empirically.

In Section 2.2 we discuss location theory, which provides detailed consideration of the factors that influence the spatial location behaviour of firms. The trend of changing location patterns of specialised economic activities was identified in Chapter 1 as being of central importance in the emergence of polycentric forms. Further insight on this issue is provided by reviewing location theory and recent research into agglomeration economies.

2.1 Land Use Transportation Interaction

2.1.1 Systems Theory

We exist in a world of vast complexity and thus our knowledge depends on methods of reduction and abstraction that provide explanation (and ideally prediction) of real world processes. A key technique in the development of scientific knowledge is modelling (discussed in more detail in Chapter 4). A model is an abstraction of reality that mediates between theory and the real world (Morgan and Morrison, 1999), enabling theoretical exploration and a means of empirical testing. Systems theory is a widely used technique for the development of models. Modern systems theory had its origin in the early to mid 20th century as a means of studying interrelationships between elements of physical, biological and social phenomena. It is in its conception an integrative approach, cutting across disciplines, and indeed contributing to new disciplines, such as the fields of cybernetics, information science and complexity theory. As systems theory is concerned with understanding and influencing processes of complex interrelationships, it has considerable relevance as an approach for the study of cities, and indeed several influential works promoting a 'systems view' of urban planning emerged in the 1960's (Chadwick, 1971; McLoughlin, 1969).

A system can be understood as a group of objects related or interacting to form a unity, or complex whole (McLoughlin, 1969). In any natural or social system no element is entirely isolated, and has connections to further systems, often at higher and lower spatial and temporal scales. The human body for instance is composed of an array of physiological systems and interrelationships, from the processes of an individual cell, to body-wide circulatory, respiratory and nervous systems. As there are many interrelationships between macro-systems and micro-systems, therefore systems need to be defined in terms of their relationships to other systems i.e. systems of systems. The measurement of a system at a basic level can take place through stocks and flows, with stocks analysing the scale of an object, and flows measuring the magnitude of an interaction. In an urban context stocks can be for example populations, jobs, and built-environment measures, while flows can be trips, migrations and financial interactions. As systems theory is concerned with relationships and feedbacks,

the dynamics of the system can be analysed in terms of temporal patterns. System feedbacks can reach a balance, producing a static equilibrium solution, or alternatively feedbacks may be unbalanced, producing an unstable disequilibrium system. This state of permanent flux and change is a characteristic of many cities, as the cycles of global economic change, business cycles, and urban development cycles interact and pull cities in different directions.

The systems approach to cities influenced scientific planning paradigms and the quantitative revolution in geography that came to prominence in the 1950's and 1960's. This academic movement was later criticised from political-economy and socio-cultural perspectives as economically determinist and politically naïve. It is important to note however that systems theory is not necessarily domain specific, and can equally be applied to urban research in theoretical opposition to the quantitative geographical approach, for instance in critical studies of capitalism. One of the most forthright and insightful critiques of 20th century modernist planning can be found in Jacob's *Death and Life of Great American Cities* (1961), where Jacobs cites the emerging field of cybernetics as a major influence on the work and as the best approach for the advancement of urban studies.

2.1.2   Defining Urban Systems: Land Use Transportation Interaction

In the context of cities, many of the processes discussed in Chapter 1 can be approached from a systems perspective, from transportation flows, to urban development and population change. Interactions between urban land use and transportation systems are the focus of this research, and are discussed here. The issue of inter-relationships between systems is particularly relevant in an urban context. Cities integrate many systems at varied spatial scales from local to global; and varied temporal scales from day to day processes, to those operating over decades. Table 2.1 lists general urban processes by temporal scale. Slow gradual processes relate to the techno-economic paradigms discussed in Chapter 1, including structural change in the global economy, demographic changes and the introduction of new technology. Fast processes include flows of

communication (which can take seconds in the digital world) and the daily cycles of urban travel (Wegener, 2004).

Table 2.1: Urban Spatial Processes and Temporal Scale. Adapted from Wegener (2004).

Fast Processes (daily or faster)	Medium Processes (less than 10 years)	Slow Processes (over decades/centuries)
Communication flows (electronic very fast) Travel patterns	Location decisions of firms and residents Urban development cycles Business cycles	Structural economic change Major demographic change Techno-economic paradigm shift

The processes influencing the spatial structure of cities in terms of land use and urban function are generally medium term temporal interactions, principally including the location choices of firms and residents, and cycles of urban development. These are in turn linked to both more rapid dynamic processes, such as travel patterns (which influence accessibility), and to slower urban processes, such as economic change (which influence the dominant forms of economic production in different urban eras). The challenge therefore in the study of urban systems is to incorporate the many inter-relationships between systems at different temporal and spatial scales, whilst bearing in mind the impossibility of 'modelling everything' and the need for analysis that is comprehensible for research and planning practice.

The earliest urban applications of systems theory were in the transportation field. Classic models based on the four stage transportation model (Figure 2.1) essentially worked by assuming land use (and medium-slow urban dynamic processes) to be fixed. Based on the existing distribution of population and employment in an urban area, transport trips could be generated, then distributed and assigned to transport modes and networks. Transport cost restrictions in terms of congestion operate by feedback mechanisms from the assignment stage to the trip generation and distribution stages.

```
        ┌─────────────────────────────────┐
    ┌──>│        Trip Generation          │
    │   └─────────────────────────────────┘
    │                   │
    │                   ▼
    │   ┌─────────────────────────────────┐
    ├──>│        Trip Distribution        │
    │   └─────────────────────────────────┘
    │                   │
    │                   ▼
    │   ┌─────────────────────────────────┐
    │   │          Modal Split            │
    │   └─────────────────────────────────┘
    │                   │
    │                   ▼
    │   ┌─────────────────────────────────┐
    └───│       Traffic Assignment        │
        └─────────────────────────────────┘
```
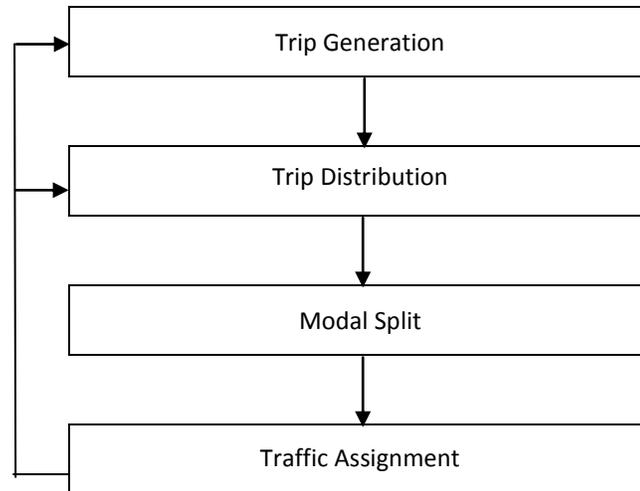
Figure 2.1: The Four Stage Transportation Model

The four stage transportation approach has proved to be very effective in predicting transportation patterns over relatively short time scales. In the simple form presented above it does not represent the behavioural aspects of travel patterns in any detail, and does not tackle the medium to long term processes of urban dynamics. As explored in Chapter 1, urban spatial structure is created through the co-evolution of land use and transport, and an understanding of urban form needs to be based on feedback cycles between land use and transportation (Wegener, 1994), as illustrated in Figure 2.2.

```
              ┌─────────────────┐
              │    Activities   │
              └─────────────────┘
              ↙                 ↖
  ┌─────────────────┐     ┌─────────────────┐
  │    Transport    │     │    Land Use     │
  └─────────────────┘     └─────────────────┘
              ↘                 ↗
              ┌─────────────────┐
              │  Accessibility  │
              └─────────────────┘
```
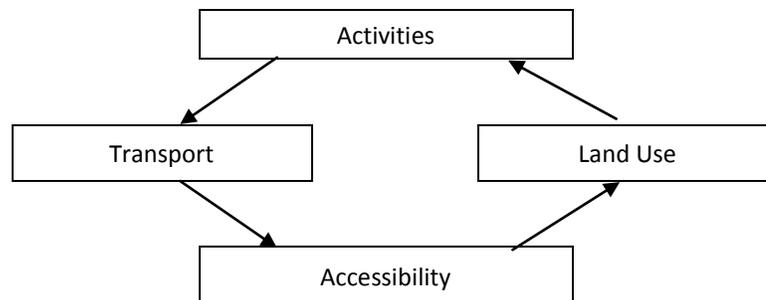
Figure 2.2: The Land Use Transportation Feedback Cycle. Source: Wegener (1994).

Thus for example, the development of new transport infrastructure such as a motorway will change accessibility and consequently land use patterns, as urban development is attracted to areas with improved accessibility (Hansen, 1959). Conversely changes in land use such as the development of a major new office

will affect activities and transport flows, changing accessibility through providing new employment opportunities and potentially increasing congestion.

The feedback cycle presented in Figure 2.2 is highly generalised, and can be expanded to consider in more detail the processes of urban development and land use. In Figure 2.3 the land use transportation feedback relationship is presented as a resolution of supply and demand for real-estate through property markets. In this system the concept of accessibility links between travel network flows (the output of the four stage transportation model) and the location decisions of firms and residents. Physical built-environment change through urban development is a connected process incentivised by rental profit. Urban planning also plays a variable role in land use decisions depending on the degree of state intervention, through policies such as planning permissions and zoning, and the development of transportation and public service infrastructure.
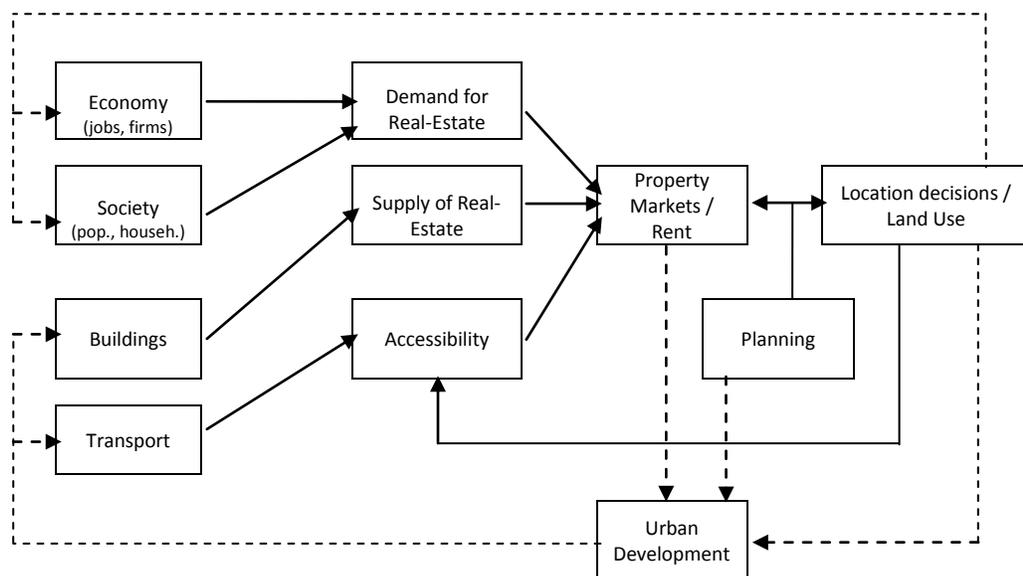
Figure 2.3: Model of Urban Land Use and Development

Urban land use and spatial structure is a major focus of this research and it is worth exploring the assumptions of the system model in Figure 2.3 in more detail. It essentially assumes that the urban economy and population is determined externally or exogenously to the urban land use process. In many senses this is true, as processes of global economic change, trade flows, migration flows, business cycles and so forth strongly affect urban socio-

economic processes and are independent from the spatial structure of cities. However the urban built-environment and socio-economic structures co-evolve together over long periods of time, and in a successful urban environment there is a close correspondence between them. The lack of correspondence between populations and the built-environment, in situations such as overheating property markets and urban decay, represents urban dysfunction. A feedback mechanism from land use to socio-economic geography is depicted in Figure 2.3, indicating how the ability of a city to facilitate the living and working demands of residential and commercial activities affects future development.

A key issue in the study of urban systems is the degree of disaggregation considered in the analysis of urban actors. Figure 2.3 implies a single system and property market for all types of households and all kinds of firms, which is clearly a gross simplification. In addition to the highly varying requirements of firms compared to residents, many further levels of disaggregation are possible, for instance families with dependent children will have very different locational priorities compared to single households, as will manufacturing firms compared to a business services firms. Urban actors can also be disaggregated along wealth lines, as their ability to pay for property has a strong influence on the location choices available. State intervention typically offsets market forces to a degree, through providing state housing, benefits and rental policies.

2.1.3   Urban Development- A Political Economy Perspective

System models of land use and transportation interaction give the impression that urban development is a rational steady process supplying the demands of firms and residents. There are however a number of phenomena illustrating conflicts and market failures in urban development, including property booms and crashes, underdevelopment and overdevelopment. The degree of state intervention in many aspects of development, including infrastructure construction, planning permissions, taxation and monetary policy, is indicative of the need to manage built-environment processes and the attempts to minimise market failure (urban planning is discussed in Chapter 3).

Real-estate is a capital investment, and thus is connected to cycles of capital and to other investment sources. Neo-Marxist theories of urban systems have sought to place urban development within analyses of capital accumulation. Harvey (1978) theorised three interconnected 'circuits' of capital investment (Figure 2.4). The central circuit is the production and consumption of goods. Excess capital from this circuit can be invested in alternative circuits of capital with the aim of improving productivity. These alternative circuits are the secondary circuit of fixed capital (including the built-environment) and the tertiary circuit of state functions. Capital for built-environment investment is therefore closely linked to the accumulation cycles of the wider economy, experiencing similar periods of growth and stagnation. Changes in market cycles are not typically smooth processes, and instead can take the form of speculative bubbles leading to crashes and asset devaluations. The recent financial crises that began in 2008 are considerably more complex than the simple model presented in Figure 2.4, yet it is revealing that the crises began with flawed lending practices in the US housing market, and has been compounded by the overexposure of many UK banks to property investment (Stiglitz, 2010).

Figure 2.4: Harvey's Circuits of Capital Model. Source: Harvey (1978).

2.1.4   Summary

Urban spatial structure is created through many overlapping systems, operating at different temporal scales. Land use results from interactions between the location demands of firms and residents and the physical built-environment, mediated by property markets and urban planning. This process is connected to the quick urban dynamics of travel patterns and flows (which influence accessibility) and the slower urban dynamics of built-environment change, and socio-economic change. A systems approach emphasises the importance of dynamics in understanding cities. Analysis needs to consider flows and change through time. As discussed in the following section, this is problematic for many traditional models of urban land use, as is the challenge of integrating systems at multiple temporal and spatial scales. The importance of property markets in land use decisions indicates that market data can be a useful input to analysis, and this is pursued in this research using new data sources (see Chapter 4). The systems approach also highlights how the decision making of individual urban actors collectively becomes a driver of change in larger spatial structure. Individual behaviour in markets can be explored via micro-economic approaches, and this is pursued in the next section.

2.2   The Micro-Economics of Firm Location

This section discusses the advantages to firms of locating in cities, and the relationships between firm location decision making and urban spatial structure. A review of location theory is presented, followed by a discussion of agglomeration economies from a micro-economic perspective. There are links to the previous section including interactions between property markets and land use, although location theory struggles to handle the dynamic nature of urban processes.

2.2.1   Industrial Location and Transportation Costs: Foundations of Location Theory

In this section we explore the extent to which transportation costs can explain the attraction of industrial activity to urban locations, as implied by the accessibility based account of urban evolution presented in Chapter 1. Three influential models of location theory are reviewed: Weber's (1909) theory of industrial location; Alonso's (1964) bid rent model of urban land use; and Christaller's (1933) central place theory. The challenges with applying these models to contemporary urban economic processes are discussed in the following sub-section.

In the industrial revolution major urban transportation hubs, such as railways and docks, attracted industries seeking to minimise the costs of inter-urban trade in materials and products. Locations close to sources of raw materials such as coal were also attractive for related industries. An influential strand of research into explaining these processes can be found in the work of Weber (1909), who theorised that industrial location was a function of the costs of transporting the physical inputs and outputs to a factory. For example industries where the raw material inputs weigh more than the goods output (e.g. the steel industry) are drawn towards locations near their input sources (e.g. coal and iron), while those industries that add weight and/or produce perishable goods (e.g. food products) and drawn towards locations nearer to their markets (e.g. urban populations). Weber formulated a highly production focussed perspective on industrial location, studying how manufacturing inputs are transformed into physical commodities (Weber, 1909). This theory is most relevant to heavy

industrial sectors where transportation costs have a significant bearing on location decisions. Weber himself realised that the focus on transportation costs was overly simplistic, and that other costs have a significant bearing on industrial location (Weber, 1909). Subsequently researchers reconceptualised his theory to explain industrial location as a product of a wider range of spatially variable input and output factors, such as labour and property (Smith, 1966).

The inclusion of rental costs in industrial location requires a more explicit model of intra-urban land use. Alonso (1964), inspired by the earlier agricultural model of Von Thunen (1826), provided the key work linking neo-classical micro-economic theory to a model of urban land use. In the model firms maximise profits, which are formulated as a function of space, rent and accessibility. Households are modelled as maximising their utility (a measure of the satisfaction gained from the consumption of goods and services) which is also determined by the space and accessibility factors. The original version of the Alonso bid-rent model assumes a monocentric city where accessibility is highest at the city centre, and declines linearly with distance from the core. All goods are assumed to be traded in the city centre, and firms that locate off-centre must transport their products to the central market. The core assumption of the bid rent model is that firms and households choose the location at which their bid rent (the land price they are willing to pay) outbids other competing uses. This is also the asking price of the landlord in the model for equilibrium between supply and demand to be reached. Firms and households trade-off accessibility (in terms of proximity to the city centre) against affordable space, which falls as rent increases. As the highest demand is for the most accessible locations, rents follow the monocentric pattern, with highest rents in the city centre. Alonso devised bid-rent curves to describe relationships between utility/profits and accessibility/space (Alonso, 1964). These curves vary for different types of firms, and for residential uses as shown in Figure 2.5.

Figure 2.5: Concentric Land Use Zones Generated by the Bid-Rent Curves for Retailing, Industrial and Residential Land Use. Source: Johnston *et al*. (2000).

A firm with higher added value per-unit-land is able to pay a higher price than one with less intensive land utilisation. So for example retail functions depend on access to customers and derive higher profits at high accessibility locations, leading to a steep bid-rent curve. Industrial functions derive some transport benefits from central locations but less than retail, and benefit in terms of economies of scale from large floor areas, creating a shallower bid-rent curve. Using the monocentric model of accessibility, bid rent theory derives a series of concentric rings of land use depending on which functions are able to pay the highest rent at distances from the centre. Alonso's model has inspired a series of urban economic modelling approaches. In more advanced variations of the model, restrictive assumptions such as perfect competition and complete information or the monocentric city hypothesis have been relaxed (Anas, 1982) and commodity flows between regions and sectors have been incorporated (Williams and Echenique, 1978).

Alonso explored competition for land between urban functions, and a further perspective on spatial competition can be found in Christaller's (1933) central place theory, examining service provision based on transportation costs to consumers. Unlike Weber's manufacturing and production focus, central place theory is concerned with consumption and service provision. And unlike

Alonso, a single economic centre is not assumed; in fact a hierarchy of urban centres is the defining geographical contribution of central place theory. Christaller studied the patterns of urban settlements in 20th century Southern Germany. In the theory settlements are considered as providers of goods and services to their hinterland populations (assumed to be evenly spread across a plain). The cost of services to consumers is a function of the purchase price plus the transportation costs of accessing the market, or central place. The hierarchies of urban centres in the model result from variations in the characteristics of services. Basic services, such as food retailing, can be provided relatively cheaply. They are based on low value-to-weight ratio goods, and are accessed by consumers relatively frequently. Therefore transportation costs represent a high proportion of consumer's total costs for basic services, and consumers will save money by accessing these services locally. The 'range' of basic services is local, which means that spatial competition between service providers occurs over small distances, and demand is most efficiently served by a high number of local market centres. In contrast to basic services, advanced services, such as a hospital or specialist goods retailers, are considerably more expensive to provide. Transport costs are a smaller proportion of total costs for consumers (and advanced services may be non-tradable), and so populations are willing to travel further to access advanced services. As advanced services are required less frequently, a larger catchment area population is needed for demand to cover service provision costs. The 'range' of more specialised services is therefore further than basic services and spatial competition occurs over greater distances. Thus a smaller number of larger more spatially dispersed urban centres serve these more specialised markets most efficiently (Christaller, 1933).

An urban hierarchy can be postulated based on the variable specialisation of services in urban centres. Christaller devised nested geometrical arrangements of settlement hierarchies designed to optimally provide services to an evenly dispersed population on a featureless plain. A hexagonal pattern of settlements is shown in Figure 2.6, mimicking the spatial patterns and distances between centres found in many historic settlement patterns. Note that this pattern is fractal, that is to say it is self-similar across several scales.

Figure 2.6: Central Place Hierarchy with Hexagonal Market Areas. Source: Christaller (1933).

The works of Weber, Alonso and Christaller are highly influential contributions to location theory. Their conceptual models explore the influence of spatially varying input factors on industrial location; the interaction between accessibility, function and rent in determining urban land use; and the importance of service specialisation in creating urban hierarchies. These models vary in assumptions and geographical scales, but share a focus on the importance of transportation costs, rational perfect markets, and a static understanding of industrial location. These characteristics can all be challenged, as discussed in the next section.

2.2.2   Critiques of Neo-Classical Location Theory

Critiques of traditional location theory can be loosely grouped into objections on methodological grounds; ideological critiques of utility maximisation and perfect market assumptions; and more general challenges relating to the lack of relevance of traditional location theory in the contemporary context of the globalised knowledge economy. On the methodological front, Weber (1906), Alonso (1964) and Christaller (1933) are concerned with transportation costs, yet do not engage with the reality of transport modes, network geography and congestion. The monocentric assumption in Alonso's (1964) model most closely represents 19th century industrial cities with radial public transport networks. Clearly it is possible for locations other than the city centre to provide high accessibility, and for there to be multiple commercial trading locations with varying accessibility advantages depending on transport modes. While Alonso's model can be reformulated using alternative accessibility functions (Anas *et al.*, 1998), it is not capable of analysing the changing factors that create polycentric forms. The dominance of a single centre is taken as given, without

considering what factors produce and maintain the advantages of that centre. Central place theory does on the other hand incorporate multiple centres, but it does not explain centre formation as a dynamic process. The nature of urban service hierarchies is fixed in central place theory, yet in reality it can shift. For instance the rise of mass car ownership has reduced transportation costs, contributing to the lowest-order traditional settlements, such as villages and small towns, losing their retail functions in favour of supermarkets and larger centres. The static nature of classic location models is clearly problematic. The equilibrium condition, where supply and demand are completely resolved in a static outcome, bears little resemblance to the perpetual flux of cities, with cycles of growth and stagnation and mismatches between supply and demand. A dynamic modelling approach is required to incorporate the flow of time as it affects decision making, and to consider the processes of urban cycles.

Further critiques of classical location theory have been more far reaching than methodological concerns, questioning whether such frameworks can ever be a useful starting point for understanding contemporary economic geography. Transportation costs have fallen significantly throughout the 20th century (see Section 3.2) while complex trends of globalisation, multi-national companies, post-Fordism and the knowledge economy (see Section 1.2) have led to comprehensive spatial reorganisations of firms and production processes. As material transportation costs have become less and less significant, transportation costs appear to play an increasingly marginal role in location decisions. This is not to say that spatial location has become irrelevant; quite the opposite. The intriguing paradox of contemporary economic geography is the economic dominance of a select number of globally connected cities and regions (discussed earlier in Section 1.2), in a world of declining transportation and communication costs. We address this question from the perspective of agglomeration economies in the following sub-section.

2.2.3   Agglomeration- Urbanisation and Localisation Economies

To understand the locational advantages of cities we need to consider the interdependence of firm location decisions, in terms of the economic advantages

of spatial clustering, information flows, the structure of firms, and patterns of innovation and creativity. These factors relate to theories of agglomeration economies. The tendency of similar economic activities to cluster together is a widely observed geographical pattern. Theories of agglomeration economies seek to explain such phenomena by analysing the benefits and costs to firms of spatial clustering produced through relationships of competition and cooperation. Similar to the neo-classical location models described previously, spatial clustering benefits include a reduction in transportation costs, but theories of agglomeration economies are much more diverse than transportation factors, including knowledge sharing, processes of innovation, communication and specialised labour markets.

Theories of agglomeration are based on the premise that positive externalities are generated to firms through spatial clustering. These externalities allow greater efficiency, productivity and/or innovation within and between firms. Following Hoover (1948), the economic processes that give rise to agglomeration are traditionally categorised into three groups: internal scale economies, localisation economies and urbanisation economies. *Internal scale economies* describe efficiency gains that occur as the overall scale of production is increased. They result from specialisation in the division of labour, cost reduction of inputs through bulk purchasing, and the use of more efficient operation methods (Graham, 2005). While scale economies are most apparent in manufacturing industries (leading to a small number of large factories) nearly all sectors include scale economies to a degree. Zero scale economies would lead to the highly unrealistic situation where every household could efficiently operate as their own producer and service provider in a 'backyard' economy (Fujita and Thisse, 1996).

External to the firm are efficiency gains through *localisation* and *urbanisation* economies (Marshall, 1890). *Urbanisation economies* refer to productivity advantages that affect all sectors, and principally occur in large population centres, i.e. cities. Firms derive benefits from the increased scale of markets, access to inputs and outputs, and from urban infrastructure. *Localisation economies* are generated through the spatial clustering of firms in narrow

economic sectors. The benefits of such proximity include the ease of communication, facilitating knowledge sharing and 'spillovers' between firms (Marshall, 1890). Firms can also share larger markets for inputs and outputs, the most important of these often being a shared specialised labour market. Finally the clustering of similar firms is also likely to increase competition and improve competitiveness.

Marshall (1890) provided one of the earliest and most influential analyses of agglomeration, describing how the clustering of specialised manufacturing firms increased knowledge sharing through processes such as shared labour markets. The increased dominance of services and knowledge intensive industries in the 20th century has placed even greater emphasis on the importance of knowledge sharing and innovation, and subsequently increased the importance of such agglomeration processes. High value activities in contemporary global city economies include financial and business services, creative industries and information technology. All of these activities involve the creation and processing of information. Knowledge sharing and specialised labour markets are therefore central to productivity. Large agglomerations attract employees with a wider selection of more specialised jobs with higher wages. Labour market flexibility is also a key means of sharing knowledge between competing firms. For example the 'churn' of labour within the City of London is estimated to be 25% annually, and is cited by managers as a vital aspect of the cluster's competitiveness (Cook *et al.*, 2007).

In parallel to micro-economic analyses of agglomeration economies, sociologically orientated research has added behavioural perspectives to understanding clustering. An important theme is the continued advantages of face-to-face contact, despite innovations in telecommunication and falling costs. Face-to-face contact is argued to provide enhanced communication in terms of quicker responses and body language; the building of relationships that allow trust and reliability to be assessed in business deals; and psychological motivation through socialising and live performance (Storper and Venables, 2004). In clusters where there is significant intra-firm cooperation (as in producer services) and fast changing information (such as in financial services)

it is clear how these communication and trust advantages are of importance. Creative industries also depend on face-to-face contact where ideas cannot be easily be codified, and greater innovation can be spurred from close interaction.

The reality of imperfect information in business decision making means that issues of trust and reputation are of importance. The quality of products from service industries is difficult to assess (unlike for instance manufacturing products), and thus trust and reputation are key to service industry operation. In research by Cook et al. (2007) surveying business service managers in the City of London, the most significant reason provided for locating in the business cluster was the importance of the location's image; i.e. a City of London address is a brand that enhances the reputation of a business. Similar processes occur in other industries where reputation and image is important, such as in advertising and many retailing sectors.

The focus on agglomeration economies has stimulated significant recent research in economic geography, adding much wider perspectives to traditional location theory. There is a risk however of agglomeration becoming an all-embracing 'buzz word' that lacks precise definition and empirical verification. Various agglomeration economies operate simultaneously, at different scales and in combination with negative spatial clustering economies such as high rents and congestion (Gordon and McCann, 2000). It is therefore difficult to isolate and measure individual factors, and distinguish between localisation and urbanisation economies (discussed further in the following section), and researchers have called for a more in-depth evidence base (Malmberg and Maskell, 2002). Furthermore the strength and scales of agglomeration economies vary considerably between locations and sectors. Global city agglomerations are by no means representative of typical service industries, and other sectors can include few local interactions and be based on regional connections (Coe and Townsend, 1998).

This research provides new empirical perspectives on the study of agglomeration, including more detailed sectoral and spatial disaggregation of firm geography to highlight which service industries have the greatest

propensity to agglomerate and gain from local interactions (see Chapter 5). Furthermore rental costs are another useful indicator of where benefits of agglomerations are reflected in market costs. Increased demand for locations with agglomeration externalities should be reflected in rental markets through bid-rent type processes. Note that studies of the interactions between firms through surveys is a necessary evidence base for understanding agglomeration processes and is not pursued in this research.

2.2.4   City Specialisation and Agglomeration Economies

Localisation and urbanisation economies at the scale of cities and regions are connected to city growth and specialisation. There are interesting debates regarding whether urban growth is most effective from a diverse or specialised economic base. The specialisation of functions also has implications for intra-urban structure, in terms of the hierarchy of economic centres within a city and their relationships.

Urbanisation and localisation economies are critical to economic activity at the city level, and affect the degree of diversity or specialisation of the urban economy. The relative importance of localisation and urbanisation economies has been an area of debate in economic geography, regarding whether urban success and innovation comes from concentration in a narrow range of economic sectors or knowledge sharing across a wider range of activities. This is complicated by the fact that localisation and urbanisation economies operate simultaneously are not necessarily clearly distinguishable. For example service firms providing intermediate inputs (such as accountancy and legal services) are considered a localisation externality in the above definition, yet these services can apply to a wide range of sectors thus making this benefit cross-sector and similar to urbanisation externalities.

According to economic base theory, the strength of an urban economy can be measured through growth and by the value of exports. Falling transportation costs and global economic integration have greatly increased potential markets for exports leading to spatial competition across larger areas and further opportunities to exploit economies of scale and localisation. Such processes can

be seen in the Fordist era where cheaper transportation and advanced mass production techniques with huge economies of scale enabled city-regions to specialise in standardised goods for global markets, such as Detroit for automobiles. In post-Fordist economies value and export markets have switched increasingly from standardised manufactured goods to services and the informational, service and creative components of manufactured goods (e.g. computer software, product design, branding).

These processes of export led scale and localisation economies encourage specialisation. Empirical studies of employment distributions find that specialisation is prevalent, particularly in smaller cities. Interestingly however growth is not necessarily related to economic specialisation. Glaeser *et al.* (1992) found higher rates of growth in cities with diversified industrial bases. Henderson *et al*. (1995) found this to be true for high technology industries but not for traditional industries. Why might this be? Jacobs argued that innovation results from diversity rather than narrow specialisation, and high levels of competition between small firms in high density environments (Jacobs, 1969). These processes are linked to the product cycle, with new emerging industries prospering in diversified metropolitan centres, while mature industries locate in smaller cities when market competitiveness depends on lower costs more than innovation. Another supporting perspective comes from the tendency for large firms to split activities between high level management and research in metropolitan centres, and routine operations in lower value peripheral locations (Duranton and Puga, 2001).

The increasing dominance of global cities such as New York, London and Tokyo indicate that both urbanisation and localisation effects have to be considered simultaneously in understanding urban economies. Such cities have a highly diverse base of economic activities in multiple sectors, but also specialise in particular activities for global markets, such as financial services and electronics. This agrees with Porter's (2000) concept of the business cluster where he argues that global competitiveness results from both inter-sector and cross-sector competitive and cooperative relationships at regional levels.

The form and degree of city function specialisation has interesting implications for urban relationships at regional scales. Central place theory is based on the hierarchical principle, where specialisation relates to city size, with large settlements providing all the services of smaller centres. Centres of the same size provide identical services and thus there is no demand for horizontal interaction. Localisation economy perspectives on urban specialisation on the other hand imply that productivity gains are made through complementary specialisation relationships between cities, leading to horizontal trade relationships. This less 'top heavy' structure promoting horizontal interaction has been called the network model (Meijers, 2007). The differences between these relationships are shown in Figure 2.7. There are clear similarities between these models of economic function and the classification of monocentric and polycentric forms at intra-urban scales discussed in Chapter 1.

Figure 2.7: The Central Place (left) and Network (right) Models of Urban Structure.
Source: Meijers (2007).

It is by no means surprising that central place ideas conflict with agglomeration perspectives, as central place theory is concerned with consumer services, and agglomeration relates to production and producer service activities. These urban functions will employ different spatial location patterns. Consumption activities are not necessarily of secondary importance. In fact the theory of the consumer city (Glaeser *et al.*, 2001) places such activities at the centre of urban growth. Rises in wages and mobility (for high skill workers) mean that residents are increasingly able to choose in which city they wish to live and work. Cities compete for high skill knowledge economy employees on key amenity aspects such as the provision of entertainment and leisure services; the provision of

public services; and the quality and speed of the transportation system. Such processes could contribute to the growth of the largest metropolitan centres with the most specialised services, whilst being counter-balanced by the high living costs and negative overcrowding externalities of the largest centres.

2.3 Chapter Conclusions

In Chapter 1 we argued that accessibility is at the core of urban spatial structure and that changes in accessibility patterns acting through transportation innovation underpinned the emergence of decentralised urban forms. In this chapter we have examined in more detail how land use and accessibility are interlinked, and how urban spatial structure is created through many overlapping systems operating at various spatial and temporal scales. Urban land use results from interactions between the location demands of urban actors and the built-environment, mediated by property markets and urban planning. These processes are connected to the quick urban dynamics of travel patterns and flows, and the slower urban dynamics of built-environment and socio-economic change.

The findings from this chapter have a series of implications for the study of relationships between urban form and travel patterns (the topic of Chapter 3) and the empirical analysis of urban spatial structure that is pursued from Chapter 4 onwards. First of all the close linkages between socio-economic geography, the built-environment and travel patterns identified in the urban land use transport system models support the analysis of all these urban dimensions simultaneously. The consideration of these dimensions in isolation is likely to miss the many interactions that these models identify. A second point is the central role of markets in the functioning of urban systems, including property markets in residential and firm location decisions, labour markets in matching jobs to employees and transport markets in influencing travel decisions. Data on market feedbacks provides insight into how effectively these markets are functioning (or failing to function) and this research looks particularly at property markets and rent data, and their links to firm location decisions and agglomeration in Chapters 4 and 5. Continuing on the firm location topic, the review of location theory and agglomeration economies highlights how

different kinds of firm have contrasting location priorities. There are powerful agglomeration forces of localisation and urbanisation in key knowledge economy industries, such as business services, finance, creative industries and information technology. These are the industries that require highly specialised labour markets, face-to-face contact and information sharing, and thus gain advantages from clustering together. In a monocentric city with a strongly hierarchical structure these high-order producer service activities would be confined to the traditional city-centre, whilst in the more polycentric network model of cities multiple centres across the city-region would be competitive for knowledge economy activities and the city hierarchy would be flatter. This is directly relevant to the point from Chapter 1 that polycentric cities can feature multiple centres with highly specialised and interrelated economic activities. These spatial structures of urban economic specialisation can be explored through analysing the geography of business sectors, as is pursued for the study area in Chapter 5. A final general point is the importance of dynamics in understanding urban systems. Cities are constantly changing and being reconfigured, and it is vital to pursue a dynamic perspective to consider flows and change through time.

Chapter 3

Sustainable Transportation and Urban Form: Principles and Evidence Base

Following the discussion in Chapters 1 and 2 of the socio-economic forces that underlie urban form, we now move to a normative assessment of what makes 'good' urban form from the perspective of environmental sustainability. This chapter addresses Research Aim 2, which is *"to define urban sustainability in relation to the transportation sector, and analyse evidence on the links between urban form and transportation environmental impacts"*. We look at sustainability as an overarching principle of urban planning, in line with current national and international planning policy frameworks. A brief critique of sustainability considers the contested nature of the concept and its varied interpretations. Sustainability is defined narrowly in this research in terms of energy security and climate change mitigation. Transportation is one of the largest sectors of the economy in terms of energy use and carbon emissions, and continues to increase as a relative share of emissions as other sectors fall, as discussed in Section 3.2.

The next stage is to link transportation sustainability to the urban spatial structure issues discussed in Chapters 1 and 2, as urban form policies are frequently promoted as a means of improving transportation sustainability. Section 3.3 reviews the research evidence base analysing relationships between urban structure and travel sustainability. The relationships between urban form and travel patterns are explored at a range of spatial scales, from the metropolitan scale to micro-scale analysis. Finally in Section 3.4 the political feasibility of policy options to improve urban sustainability is discussed.

3.1   Sustainable Urban Planning

3.1.1   The Role of Urban Planning in the UK

Planning and urban policy in capitalist economies can be defined as state intervention and regulation in land and property markets. This includes managing planning permissions and development control; developing infrastructure such as transport; and developing and managing property in the case of market failure (for instance state housing). Such actions are designed to be in the public interest (e.g. DoE, 1999, p.2) yet of course the definition of the public interest is politically contested, and the question of 'planning for whom' is at the heart of debates over the role of planning. The initial impetus for land use planning came from the dire social conditions and inequalities in 19th century industrial cities. For instance in Manchester in the 1840's life expectancy for the working classes fell to 17 years (Chadwick, 1842). These concerns eventually prompted national political responses in public health, housing and sanitation reform in the late 19th century, and fuelled early urban planning movements. Industrial philanthropist reformers such as Owen, Cadbury and Lever, developed new towns for their factory workers, and this influenced the garden city movement seeking to establish independent community-owned settlements on a wider scale (Hall, 1998a).

A significant government role in planning was not established until the 20th century, in tune with wider intervention in the economy through early welfare state development. Following housing acts and plans for major cities (such as Abercrombie's Greater London Plan of 1944), planning was formalised in the UK 1947 Town and Country Planning Act. This established the planning permission and development control systems, alongside local authority development plans (Pacione, 2009). Another long established role for planning policy in the UK is urban containment. Abercrombie set up the Campaign to Protect Rural England in 1926, and greenbelts were legally formalised in 1955. The long running support for urban containment policies can be attributed to Britain's limited land supply as well as cultural factors such as a general conservatism and attachment to the 'rural idyll'. Many Western European

countries have adopted similar policies, whilst in the USA, with abundant land supplies and free-market ethos, there is little history of urban containment.

In the second half of the twentieth century urban planning has evolved through various cultures and doctrines, reflecting shifting paradigms and goals of the state (Hall, 1998b). Very briefly, a static physical and design orientated view of planning based on modernist principles was replaced by a more scientific and dynamic systems orientated view from the 1960's onwards (Batty, 1994). Both of these perspectives considered planning as a largely a-political exercise by experts. This consensus fell apart in the economic crises and political conflicts of the 1970's, where social welfare and consensus planning ideologies emerged in response to Marxist critiques of planning as a tool of capitalism. Further challenges to the role of planning came in the 1980's with the politics of the New Right, where market mechanisms were favoured over state intervention, and planning was directed towards attracting private investment (Hall, 1998b). Private sector led growth perspectives remain influential in current paradigms, though are promoted more as partnerships between the state and private sector.

In summary, planning manages land use decisions, negotiating between economic, social and environmental demands in the interests of government. It is intended to act in the public good, though interpretations of the public good vary with political movements, cultures of planning, and the nature of the state.

3.1.2   The Principles of Sustainability

Concerns that industrial development has been, and continues to be, detrimental to the earth's ability to sustain life began to rise as a mainstream political agenda from the 1960's onwards. These concerns included the limits of natural resources such as food and energy, as expressed in works such as *The Limits of Growth* (Meadows and Meadows, 1972). Conservation movements were given added impetus with improved understanding of the earth's ecosystems (Lovelock, 1979) and of biodiversity (Soule and Wilcox, 1980), and were defined in global statements such as the World Conservation Strategy (IUCN, 1980). The impacts of chemical pollutants at a local level were highlighted in works such as Carson's (1962) *Silent Spring*, and increasingly the potential for

human impacts to effect global environmental processes was realised. Concerns over anthropogenic climate change led to the formation by the UN of the Intergovernmental Panel on Climate Change in 1988 (Houghton *et al.*, 1990). Key aspects of environmental conservation- including mitigating climate change, ecosystem preservation and natural resource management- are discussed below.

Global mean temperatures are calculated to have risen by 0.74ºC in the last 100 years, and this has largely been attributed to the rise of atmospheric greenhouse gases, with the most significant greenhouse gas carbon dioxide rising from preindustrial concentrations of 280 parts per million to 379 parts per million in 2005 (IPCC, 2007). The detailed environmental impacts of future climate change are notoriously hard to predict, with considerable spatial variation in climate change impacts likely across the globe. For example, 20th century temperature rises were spatially heterogeneous with increases in the Arctic twice the global average (IPCC, 2007). There are many regions of the world that are socially and environmentally vulnerable to climate change, with the potential for more frequent droughts and reduced agricultural yields in arid and semi-arid regions (exacerbating existing poverty relationships), and threats to coastal settlements from sea level rise. In addition to highly exposed coastal countries such as Bangladesh, many of the world's megacities (with populations of over 10 million people) are situated in vulnerable coastal locations (Klein *et al.*, 2003). In addition to these medium term humanitarian vulnerabilities, in the longer term there is the potential for temperature rises to trigger feedback mechanisms in the global environment (such as methane release from the permafrost) that could produce more severe and irrevocable climate change.

The majority of greenhouse gas emissions (56%) are the result of fossil fuel use, with agriculture and deforestation also contributing significantly (IPCC, 2007). Thus there are close connections between climate change mitigation and natural resource management. Oil, natural gas and coal continue to provide the vast majority of energy supplies in both core economies and NICs. Fossil fuel energy systems are not only highly significant environmentally. The comprehensive dependence of developed countries on fossil fuels for the

operation of the economy and basic services (e.g. food supply) means that their finite nature is a significant threat to global economic and political stability. Oil supplies are the most immediately uncertain in the short to medium term. The main international body that researches this issue, the International Energy Agency, does not predict global oil production to peak before 2030 (IEA, 2008), though this conflicts with several research studies predicting a supply peak between 2010 and 2020 (Hirsch, 2007). This unpredictability results from considerable uncertainty over total supplies, the exploitation of non-conventional oil sources and further uncertainty over demand.

Oil supply is of course an explosively geo-political issue as dwindling western reserves (domestic production has already peaked in the USA and UK) are leading to an increasing dependence on the Middle East and to other resource rich states such as Russia. The oil crisis of the 1970's and price shock of 2008 indicate that existing market volatility will likely increase with the combined factors of limited supply and increasing demand from rapid NIC growth. If the more negative scenarios of very high energy costs do occur, then the future economic competitiveness of cities will be increasingly linked to energy efficiency and alternative energy technologies. The environmental sustainability aims of limiting natural resource exploitation are in this context broadly consistent with energy security and economic efficiency concerns.

In contrast to oil and gas, significant coal reserves remain in much of the developed and developing world, and it is currently the fastest growing fuel source with a 60% increase predicted by 2030 (IEA 2008). This energy source is the most polluting fossil fuel in terms of carbon emissions as well as pollutants such as sulphur dioxide (a major source of acid rain) and release of particulates damaging to human health. As oil and gas supplies stagnate or fall, coal use will increase with environmental consequences both for climate change, habitat destruction and pollution. The potential technological fix of carbon capture and storage technology would be a major breakthrough in mitigating the climate impacts of fossil fuel power stations, but it is at present a non-operational technology, and severe doubts have been expressed over its economic feasibility (Al-Juaied and Whitmore, 2009). Given these limitations,

current sustainable energy policies focus on improving energy efficiency, renewable energy and, controversially, nuclear power.

In more arid regions of the world, the key natural resource limitations are fresh water and fertile land. The earth's ecosystems are critical natural resources- for their roles in environmental cycles and biodiversity. At the most basic level, we depend on photosynthesis for oxygen, and there are a range of further natural cycles, including the role of many ecosystems as carbon sinks, particularly oceans, forests and tundra. The desire to preserve biodiversity comes partly from the moral imperative to preserve the life of species. While extinction is a natural process that has occurred throughout earth's history, it has been dramatically accelerated by habitat destruction, deforestation, pollution and likely anthropogenic climate change. The rich biodiversity of many ecosystems also contains many applications for science and medicine.

The three environmental topics discussed above - mitigating climate change, natural resource management and biodiversity - represent fundamental concerns of environmental sustainability. As the current threats to these environmental systems are mainly anthropogenic, clearly sustainability depends on interactions between the environment and human society. The concept of *sustainable development* attempts to integrate the demands of environmental sustainability with human needs as depicted in the 'three pillars of sustainability' diagram (Figure 3.1). The most commonly cited definition of sustainable development comes from the United Nations World Commission on Environment and Development (1987), commonly referred to as the Brundtland Report, as: *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* (WCED, 1987, p.43). This includes the principles of intra-generational equity (equality across the current world population) and inter-generational equity (preserving finite natural resources and ecosystem health for future generations). The latter concept is connected to environmental *carrying capacity*, or the degree to which resource use is within natural regeneration limits.

Figure 3.1: The 'Three Pillars' of Sustainable Development.

The term sustainable development is often criticised. Its meaning is somewhat ambiguous, and at worst has been described as an oxymoron (Lele, 1991). The Brundtland Report discussed relationships between environmental sustainability and alleviating global poverty, thus development in this context referred to addressing global inequality and the needs of less developed countries. The report supported economic growth as an essential means to improve the livelihoods of peoples in the global south. It also argued that economic growth is compatible with environmental sustainability as it provides the means to manage natural resources and to stabilise populations, as falling birth rates are linked to improved education and life expectancy levels (WCED, 1987).

The complexities of global development are beyond the scope of this research, and we instead focus on the importance of sustainability for policy making within the UK. In core economies the term sustainable development is often used somewhat ambiguously to imply *sustainable economic growth*, indicating that sustainability can be achieved within the current capitalist framework of prioritising economic expansion. As per-capita environmental emissions and resource use in the developed (and increasingly the newly industrialised) world are several times higher than less developed countries, environmentalists frequently disagree that environmental sustainability can ever be compatible with a high growth strategy. The debate surrounds whether economic growth can be 'decoupled' from intensive resource use and emissions. In the so-called

'weak' definition of sustainability, economists argue that natural capital is replaceable through technological innovation, and that as natural resources decline, market price rises will stimulate the creation of alternatives. This is generally an argument in support of business as usual, or of moderate change, e.g. pricing environmental externalities. In contrast the 'strong' definition of sustainability contends that many natural capital stocks are irreplaceable, and there are no man-made substitutes (Rees, 1992). This definition leads to more radical conservation and market intervention policies. Due to the ambiguity of the term sustainable development, it is not used in this research, and instead we focus on the term sustainability as shorthand for environmental sustainability, referring to the climate change mitigation and natural resource management issues discussed above.

Currently the harmonious relationship between the environment, society and economy depicted in Figure 3.1 bears little resemblance to reality. The processes of advanced capitalism and globalisation (described in Chapter 1) have been closely tied to fossil fuel use, resource depletion, habitat loss and high carbon emissions. International agreements on sustainability issues have thus far been limited. On the key issue of climate change, the Kyoto protocol of 1997 was the first major international treaty setting carbon emission limits, yet despite the relatively modest targets the agreement failed to be ratified by the world's two largest economies, the USA and China. More recent attempts for a comprehensive agreement in Copenhagen 2009 included all major economies but ended without any legally binding emission reduction targets. International progress is more plausible where developed economies can deliver large reductions and move towards greater global equality in per-capita emissions. Arguably therefore the current stalemate should not deflect efforts in developed countries to reduce carbon emissions. Furthermore the aims of climate change mitigation are in accordance with the wider environmental sustainability and economic goals of more efficient resource use and increasing energy security.

In summary environmental sustainability addresses the key issues of natural resource management, biodiversity preservation and mitigating anthropogenic climate change. Sustainability impacts are embedded in wider relationships

between the environment, human society and the economy. Climate change is intertwined with issues of global inequality and capitalist power relationships, and thus far the international political consensus on climate change mitigation is limited. International agreement is more likely where developed economies can deliver large reductions and move towards greater global equality in per capita emissions. The aims of climate change mitigation, i.e. reducing fossil fuel use, are largely in accordance with those of energy security and efficient resource use.

3.1.3   Sustainability Policy and Planning

Sustainability relates to all aspects of the economy and society, from agriculture to production, consumption, international trade and energy generation. Urban systems play a critical role in many aspects of sustainability as cities are the great concentrations of socio-economic activity. Subsequently the vast majority of energy use, carbon emissions, water use, land use, pollution and waste production results from the demands of urban residents and firms. This demand is either directly from urban activities, or indirectly through resources used in the production of goods consumed in urban markets. Thus urban planning has an absolutely central role in achieving a more sustainable economy and society.

In light of scientific evidence and political change, UK planning legislation in 1990's began to be reformulated around sustainable development discourses. Following the 1992 Rio Earth Summit the first UK sustainable development strategy was published in 1994 (Cullingworth and Nadin, 2006). One of the most significant changes in policy came from transportation in Planning Policy Guidance Note 13 (DoE, 1994), which explicitly sought to reduce car travel through integrated land use planning (particularly less out-of-town retail), car parking policy and a fuel duty 'escalator' of 5% per annum (later abandoned in 2000). While these policies had multiple aims including the preservation of traditional town centres and congestion reduction, the adoption of the sustainability discourse was a significant change. Subsequently all planning legislation has been redrafted around the sustainable development agenda (DoE, 1997; ODPM, 2005) (Table 3.1). The full range of national planning policy statements on economic development, housing, rural development, greenbelts,

energy, waste, regional planning, flooding risk and biodiversity has been reformulated. Another important urban planning policy document for the UK was the influential Urban Task Force report *Towards an Urban Renaissance* (1999), which promoted compact city ideas in the context of regenerating and repopulating struggling city centres.

Table 3.1: Sustainable Development and Planning Principles of the UK Government

Sustainable development principles of UK government (1999)	Planning principles for achieving sustainable development: (ODPM, 2005)
- Social progress which recognises the needs of everyone; - Effective protection of the environment; - The prudent use of natural resources; - The maintenance of high and stable levels of economic growth and employment. These aims should be pursued in an integrated way through a sustainable, innovative and productive economy that delivers high levels of employment, and a just society that promotes social inclusion, sustainable communities and personal well being, in ways that protect and enhance the physical environment and optimise resource and energy use.	Making suitable land available for development in line with economic, social and environmental objectives to improve people's quality of life; Contributing to sustainable economic development; Protecting and enhancing the natural and historic environment, the quality and character of the countryside, and existing communities; Ensuring high quality development through good and inclusive design, and the efficient use of resources; Ensuring that development supports existing communities and contributes to the creation of safe, sustainable, liveable and mixed communities with good access to jobs and key services for all members of the community.

It is apparent from the policies in Table 3.1 that the UK government's definitions of sustainable development incorporate economic growth. Thus this is the 'weak' interpretation of sustainability, as opposed to a stronger interpretation that would be willing to prioritise environmental sustainability potentially at the expense of economic growth. The vague meaning of the term sustainable development suits governments in this regard, as the definition can potentially be shifted to comply with preferred decision making. Arguably in a number of high profile planning issues environmental priorities are considered of secondary importance to economic demands. For instance airport expansion was promoted in the UK over the last decade in spite of environmental impacts due to positive impacts on jobs and economic growth. As a consequence carbon emissions from this sector increased significantly. In light of the contested nature of sustainability, decision makers and the public require a comprehensive and transparent evidence base on which to assess policies, as discussed in the next sub-section.

3.1.4   Measuring Urban Sustainability- Integrated Urban Assessment

The ambiguities of sustainable development and planning policy can to a degree be minimised with the measurement and application of a transparent evidence base of economic, social and environmental indicators. A comprehensive evidence base will not resolve planning conflicts, but it can improve decision making with a more informed understand of the processes and impacts involved, and ideally enabling the understanding of the interrelationships and consequences of policies. A significant part of this research is concerned with the calculation of indicators related to the environmental impacts of transportation, and it is necessary to understand how such indicators can fit into a comprehensive framework of urban sustainability assessment. Issues include the comprehensiveness of indicators, bridging between environmental and socio-economic dimensions, defining the extent of studies, and including urban dynamics, as discussed below.

Clearly one of the major challenges of sustainability assessment is the multitude of factors to be considered together. Even within the environmental impact domain, a host of issues from air pollution, water quality, energy use, waste, flooding and biodiversity need to be considered. The systems perspective introduced in Chapter 2 is a very useful tool for assessment. Several systems techniques have been developed for the integrated assessment of urban sustainability, including urban ecosystems, urban metabolism, environmental space and ecological footprints (Ravetz, 2000). The systems perspective leads to a focus on inputs, outputs and resource flows. Furthermore there is a need to connect environmental impacts to the socio-economic demands that lead to such impacts, so that processes of causality can be assessed. Sectoral disaggregation is a straightforward first step in this task (as pursued in the following sub-chapter), as is the link between micro-level behaviour and system wide impacts.

It is vital to consider dynamics in the assessment of urban systems, allowing the study of trends and where processes are moving towards. Useful set of indicators should be able to tell (1) whether urban quality and performance in cities is improving or deteriorating in relation to certain sustainability criteria or desirable targets, and (2) how these trends in urban quality and performance are

linked to trends in spatial structures, urban organisation and lifestyles (Alberti, 1996). A further challenge in urban sustainability assessment relates to the defining system boundaries. Attempting to isolate aspects of sustainability assessment is problematic due to the continuous interactions of urban sub-systems into complex wholes. An obvious example for cities concerns international trade. Importing goods from outside the city system adds the materials and energy used in the production of those goods should to the city's consumption, but this is challenging to measure. As the interconnectedness of cities increases with multi-national firms, global financial systems and more intensive trade and information flows, the challenge of defining system boundaries becomes more difficult.
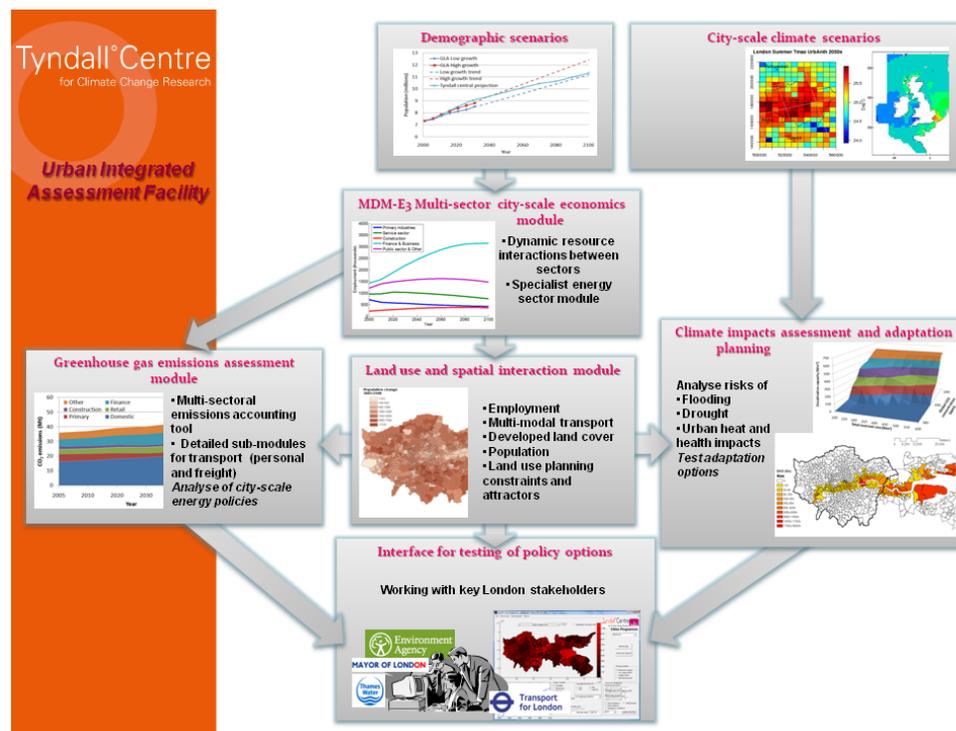
Figure 3.2: Integrated Urban Assessment Model. Source: Hall *et al.* (2010).

An example approach to integrated urban assessment in relation to land use planning is shown in Figure 3.2. This is the Urban Integrated Assessment Framework from the Tyndall Cities research programme (Hall *et al.*, 2010). It involves a series of sub-models that interact through feedbacks. Demographic and economic scenarios (at the top of Figure 3.2) drive a land use model of residential and commercial activities (in the centre of Figure 3.2), which in turn

underlie travel patterns. Land use patterns influence both emission scenarios and risks to climate change hazards. Thus the assessment framework aims to include dimensions of climate change mitigation (how cities contribute to green house gas emissions) and adaptation (how cities are vulnerable to changing climates). Potential synergies and conflicts and mitigation and adaptation policies can be assessed together. This research thesis addresses several aspects of this complex integrated urban assessment whole, namely connections between economic geography, accessibility and travel patterns; between transportation and greenhouse gas emissions; and the communication of sustainability impacts through spatial indicators.

3.1.5   Summary

Environmental sustainability addresses the key issues of natural resource management, biodiversity preservation and mitigating anthropogenic climate change. Sustainability impacts are embedded in wider relationships between the environment, human society and the economy. Climate change is intertwined with issues of global inequality and capitalist power relationships, and thus far the international political consensus on climate change mitigation is limited. International agreement is more likely where developed economies can deliver large reductions and move towards greater global equality in per capita emissions. The aims of climate change mitigation, i.e. reducing fossil fuel use, are largely in accordance with those of energy security.

Urban systems play a critical role in many aspects of sustainability as cities are massive concentrations of socio-economic activity, resource use and carbon emissions resulting from the direct and indirect demands of urban populations. Thus urban planning has an absolutely central role in achieving a more sustainable economy and society. Planning policy has been redrafted around the sustainable development agenda, though there is much ambiguity in the concept of sustainable development. Generally the 'weak' definition of sustainable development is employed, incorporating economic growth. The complexities of sustainable development require a transparent evidence base of economic, social and environmental indicators for policy analysis. The many connections and feedbacks support an integrated urban assessment framework approach.

3.2 Transportation and Sustainability

This section begins with a discussion of the nature of travel demand, and how the processes that underlie travel demand relate to the comprehensive change in UK travel patterns over the last half century. We then examine the environmental impacts of transportation in terms of energy use and carbon emissions, and how these are correlated with travel characteristics. The final section discusses the potential for technological change such as the electrification of automobiles to 'green' private transport.

3.2.1   The Nature of Travel Demand

Transport clearly has an essential social role in linking communities and social groups together, and an essential economic role in allowing businesses to function. It is mainly a derived demand; that is to say the value of travel comes mainly from the utility of accessing a destination, rather than the intrinsic value of travel itself. There is also an inherent value in travel, in terms of the physiological and social benefits such as exercise and a change of environment. This value has traditionally been downplayed in research, though the role of intrinsic value in travel behaviour is increasingly recognised as being significant in some aspects of travel behaviour (Mokhtarian and Salomon, 2001). Overall, the demand for transport is a product of the activities that populations and businesses wish to pursue, and where they wish to pursue them.

Travel demand is constrained by the costs of travel, mainly in terms of time and money. Research provides strong evidence that individuals maximise the activities or opportunities that can be reached within their time and financial budgets (Zahavi and Talvitie, 1980). Over the last half century as mobility has increased and wages have risen, a possible travel demand response could have been for individuals to follow similar journey patterns whilst saving time and money. Yet this clearly has not happened. Instead travel distances have greatly increased to maximise the spatial opportunities available to populations. Travel

time budgets have been argued to be relatively stable, with populations taking advantage of increased mobility to travel further- a phenomena dubbed the 'law of constant travel time'[1] (Hupkes, 1982). The behavioural pattern of maximising travel opportunities can be seen in the explosive growth of private travel in the UK, as shown in Figure 3.3.
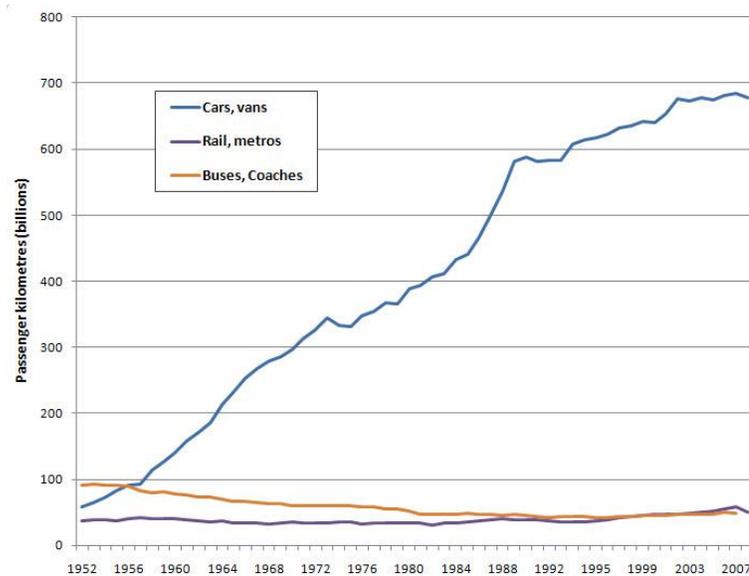
Figure 3.3: UK Total Travel Distance by Mode 1952-2008.
Data source: Department for Transport (2009b).

In the second half of the twentieth century the UK has experienced significant economic growth with rising wages, the mass market adoption of cars, falling fuel costs and a resulting decrease in motoring costs. This is linked to the revolution in residential lifestyles with widespread suburbanisation, and is also connected to processes of economic specialisation and commercial decentralisation (see Chapter 1). The growth in travel distances is overwhelmingly private transport based, with a five-fold increase since 1960,

---

[1] There are exceptions to the stability of travel time budgets, such as the trend of 'extreme' commuting. The development of mobile information technology and communication has allowed some trips to be more productive, and this can result is increased distances as the intrinsic value of time spent travelling increases.

while in contrast public transport has fallen significantly. The dominance of the automobile is related to a range of factors, including decentralisation in the spatial form of contemporary cities, large-scale state investment in road infrastructure, the advantages in comfort and flexibility that cars confer, and demographic changes such as the increasing number of two-worker households (Banister, 2005). Increased private transport is closely connected to greater affluence and mobility for large sections of the population. Cars are significant status symbols, and many cultures and lifestyles have developed based on automobile travel. Interestingly Figure 3.3 also shows new patterns emerging in the last decade with private transport levelling off and rail use rising slowly (note that this public transport growth trend is significantly more pronounced in London).

The pricing of private transport has also played a role in its spectacular growth. Road transport is problematic to price efficiently. Roads are public goods that are free to travel on, and therefore, once an individual or household has purchased a car, the only major financial cost constraint on car travel is fuel. The desire of travellers to maximise opportunities by increasing travel distances in combination with economic growth and public good pricing has meant that that as road capacity expands, car travel also increases through so-called induced demand. This expansion continues until capacity is reached and demand is curtailed by congestion. UK transport policy has turned against road expansion in the last fifteen years, resulting in the declining speeds shown in Figure 3.4 and contributing to the recent stabilisation of private vehicle miles.

In summary individuals use transport to maximise opportunities, and will travel further as costs fall. Decreasing motoring costs over the last half century have led to an explosion of private transport use in the UK, with a five-fold increase since 1960. The growth in travel distances is comprehensively private transport based, and public transport has fallen significantly. Over the last ten years private transport miles have stabilised and public transport has begun to increase, reflecting high levels of congestion and changes in government policy.

Figure 3.4: Average Traffic Speeds in English Urban Areas 1999-2006.
Source: Department for Transport (2009c).

3.2.2   Urban Transportation and Sustainability

This research focuses largely on urban transportation sustainability and
efficiency. Transportation is a major source of energy use and of carbon
emissions, and has increased in relative terms as carbon emissions have fallen in
other sectors. The dynamics of energy use by sector over time can be used to
illustrate the changing nature of the UK economy. Figure 3.5 graphs energy use
by sector in the UK between 1970 and 2008. Alongside falling levels of
industrial energy use from deindustrialisation, the main change has been the
doubling in transportation energy use, reflecting the huge expansion of
automobile travel described in the previous section, in addition to increased air
travel.

(1) Services include the commercial sector, public admin and agriculture.

(2) Industry includes construction

Figure 3.5: Final Energy Consumption by Sector. Source: DEFRA (2009).

Energy use can be traced to fuel sources to consider fossil fuel and energy security perspectives. A diagram tracing energy flows from sources to final consumption is shown in Figure 3.8. The UK transportation sector is overwhelmingly dependent on petroleum, accounting for over 98% of all transport energy used (illustrated by the blue flow in Figure 3.8). This overwhelming petroleum dependence and the scale of transport energy use are a clear environmental and energy security hazard. As carbon emissions are closely related to fossil fuel energy use, it follows that transportation is also a major source of carbon emissions. Domestic carbon emissions by sector for the UK in 2005 are shown in Figure 3.6, with transportation forming 27.4% of end user emissions (not including international air travel). Cars use accounts for 54% of the transportation total, whilst goods vehicles contribute a further 35% (Figure 3.7).

Figure 3.6 & 3.7: UK Carbon Dioxide Emissions by Sector 2005 (left) and UK Transport Carbon Dioxide Emissions by Mode 2005 (right). Source: DEFRA (2007).

Figure 3.8: UK Energy Flow Chart 2007 (units: millions of tonnes oil equivalent) (Dept for Business Enterprise and Regulatory Reform, 2007)

Despite the trend of increasing vehicle miles in recent decades, carbon emissions from domestic transport have only marginally increased since 1990 (Figure 3.9). This is a result of improved efficiency in the vehicle fleet. In relative terms the contribution of domestic transport to UK carbon emissions has increased as other sectors have benefitted from the decreasing carbon intensity of electricity generation. This has occurred from a reduction in UK coal based electricity generation, mainly in favour of natural gas generation, as can be seen in the Figure 3.6 energy flow diagram in the approximately equal contributions of coal and natural gas to power station inputs.

Figure 3.9: Carbon Dioxide Emissions by Sector for UK, 1990 to 2007. Source: DEFRA (2009).

In summary transportation sector is a major source of energy use and carbon dioxide emissions. Carbon dioxide emissions have increased in relative terms as emissions from other sectors have fallen, whilst transportation is largely stable in absolute terms in the last ten years. Transportation is at present overwhelmingly petroleum based which presents considerable environmental and energy security risks.

3.2.3 Mode-Choice, Carbon Dioxide Emissions and Technological Advances

The energy use and carbon emissions for particular transport journeys are largely a product of mode-choice and distance travelled[1] (Banister, 2005). The UK government calculates mode specific estimates of carbon emissions per-passenger-kilometre travelled as shown in Figure 3.10. These calculations include detailed analysis of the UK vehicle fleet and public transport systems; empirical analysis of typical road conditions and driving behaviour; emissions resulting from the processing of fuels; and CO2 equivalent emissions from other greenhouse gases such as methane and carbon monoxide (DEFRA, 2010).
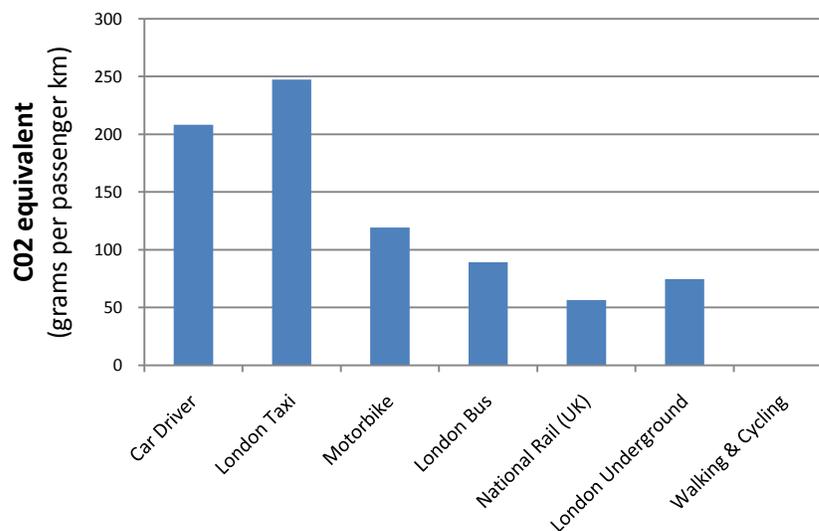
Figure 3.10: Estimates of Carbon Dioxide Emissions Per-Passenger-km by Private and Public Transport Modes. Source: DEFRA (2010).

Cars and taxis are the least efficient modes with average per passenger kilometre emissions between 2-3 times larger than for public transport modes. Public transport has lower, but not insignificant, per-capita emissions due to the

---

[1] Note this relationship describes the direct energy use and carbon emissions from journeys. There are also indirect carbon emissions resulting from processes such as vehicle manufacture and infrastructure development that are not considered in this journey specific approach.

greater capacity of public transport vehicles, with national rail being the most efficient mode. Walking and cycling have been included in the graph assuming they have zero direct carbon dioxide emissions, and this assumption is maintained throughout this research. Occupancy is a key factor for all modes. In Figure 3.10 the occupancy of cars is assumed to be 1 (which is close to reality for London as demonstrated in Chapter 6) whilst the public transport emissions are based on average occupancy figures for these modes. The spatial and temporal variation in occupancy creates an added complication for journey-specific carbon emissions modelling (see Section 4.4).

Responding to these carbon and energy impacts, policies for sustainable transport are geared towards minimising journey distances and reducing car use in favour of public transport, walking and cycling. There are various synergies between these policy goals, as for example shorter journey distances are more conducive to walking and cycling, and public transport and pedestrian travel are largely complementary. The energy and carbon characteristics of motorised transport modes are not necessarily fixed however, as they are significantly determined by the technologies in use. A major technological revolution is currently underway in converting automobiles from petroleum based internal-combustion engines to electric drive-train vehicles, including electric plug-in, hybrid and hydrogen fuel cell technologies (Banister, 2005). This begs the question of whether such breakthroughs will significantly alter the energy efficiency and carbon emission profiles of private vehicles. There are many advantages associated with electric driver-train vehicles. The removal of local air pollution from vehicles will be a significant quality-of-life improvement in urban areas, as private transport is a major source of local pollution. Electric motors are also considerably more efficient than internal combustion engine technologies, and carbon emissions should fall. Another important issue is the prospect for the electrification of vehicles to reduce direct transportation dependence on oil supplies.

The advance of electric drive-train vehicles is not however a panacea in terms of private transport. Efficiency gains from electric motors are reduced by the energy use and carbon emissions produced in the generation of electricity.

Whilst greater renewable electricity generation would solve this, current predictions for the UK renewable electricity generation are only 12% by 2020 (DECC, 2009), and even this modest figure may not be achieved. Battery technology at present limits electric cars to approximately 100 miles range, and considerable energy is lost in the charging and operation of batteries. Hydrogen fuel cell technology is currently considered the long term solution to private vehicle travel as illustrated in Figure 3.11, but several technological hurdles remain, and an entirely new energy infrastructure would need to be constructed for the technology to be operational. Banister (2005) estimates that in 2030 only 20% of the vehicle fleet will be electric-drive-train, due to the massive capital investment in existing vehicle technology and infrastructure. This represents poor progress from both climate change mitigation and energy security perspectives.

Figure 3.11: Schematic Diagram of Technological Advances Required for Low Carbon Vehicles. Source: Department for Transport (2009).

The environmental impacts of private transport will therefore be reduced by electric vehicles but not removed. Furthermore it will likely take decades before the vehicle fleet has shifted significantly to low carbon technologies. This means that the policy focus on reducing car use in favour of other modes should remain the priority. Electric powered public transport modes in the form of contemporary trains and trams are widely in use (though limited in the UK) and will retain efficiency advantages over electric drive-train vehicles for most urban contexts. Finally walking and cycling will of course remain more

environmentally benign choices than any motorised mode. Another issue to consider in relation to technological advances is the potential for new and reconfigured transport modes to emerge. For example the moves towards smaller city cars may eventually result in dramatically smaller vehicles or 'micro-vehicles' with significant environmental and congestion benefits. Other trends include electric supported pedal bikes, and the potential for self-driving flexible public transport. It is beyond the scope of this research for a full discussion of potential changes, but it is worth noting that the emergence of new modes of travel is a distinct possibility.

In summary energy use and carbon emissions in the transportation sector are closely correlated with travel distances and mode-choice. Policies for sustainable transport are geared towards reducing journey distances and reducing car use in favour of public transport, walking and cycling. A major technological revolution is currently underway in converting automobiles from petroleum based internal-combustion vehicles to electric drive-train vehicles. The environmental impacts of private transport will be curbed through electrical technologies but not removed. The relative environmental advantages of public transport, walking and cycling are very likely to remain in place.

3.2.4   Environmental Impacts and Trip Purpose: the Significance of Journey-to-Work

Travel demand is related to activities and trip purposes. Common trip purposes include journey-to-work, journey-to-school, shopping, escorting children, business travel, personal business travel (e.g. bank, post-office, health), leisure and social travel. The relative frequency of these trips for individuals will depend on the socio-economic characteristics of individuals and households such as age and family situation. This thesis seeks to investigate relationships between employment geography, urban form and sustainable travel patterns. Journey-to-work, and other related business travel, is the main focus. In this section we discuss the relative importance of work related travel in the context of general transportation sustainability.

Commuting has declined relatively as a proportion of total trip miles, and in the UK now represents 16% of trips and 19% of trip miles (Department for Transport, 2008). From these indicators journey-to-work is a minority of total travel. There are however several reasons why journey-to-work and employment related travel more generally are significant in terms of environmental and economic impacts. Firstly, employment location is connected to a series of trip purposes in addition to commuting (such as business, shopping, education and health travel) that together contribute to the majority of private trip miles and carbon emissions. As shown in Figure 3.12, a recent study by the Department for Transport found that trip purposes directly connected to employment (journey-to-work and business travel) contributed a third of carbon emissions from household cars, while those trips indirectly connected to employment locations (shopping, education and personal business) contributed to a further third of carbon emissions (Department for Transport, 2009a). Therefore trips involving destinations that are places of employment represent two-thirds of travel carbon emissions by this measure.

Figure 3.12: Estimated UK Carbon Dioxide emissions from Household Cars, by Trip Purpose and Distance, 2002/2006 Average. Source: Department for Transport (2009).

Looking more narrowly at journey-to-work, there are also specific characteristics of commuting that increase its significance in terms of environmental impacts. Certain trip purposes are relatively flexible in their destinations. So for example many shopping and leisure trips are substitutable, and could be made to various alternative locations. Increases in the price of travel are likely to have the greatest impact on these more flexible journeys.

Journey-to-work on the other hand is more fixed and regular, and personal travel patterns can only change with a major shift in lifestyle, such as moving house or a change in job. Therefore journey-to-work travel is connected to long term employment and residential location patterns. The regular nature of journey-to-work also makes it a primary candidate for public transport travel (Horner, 2004). The temporal and spatial regularity of journey-to-work travel plays to public transport's advantages in serving high density flows with timetabled services. Conversely temporal regularity is problematic for private transport which is less spatially efficient and leads to congestion, longer journey times and increased carbon emissions. For the UK as a whole currently the proportion of commuting travel by single occupancy cars remains very high as shown in Table 3.2. Other trip purposes generating large volumes of car travel include leisure, shopping and business trips.

Table 3.2: UK Travel Distances by Trip Purpose and Mode 2008.
Source: Department for Transport (2008).

3.2.5   Summary

The transportation sector is a major user of energy and source of carbon emissions, and has increased in relative terms as carbon emissions have fallen in other sectors. Transportation is at present overwhelmingly petroleum based. Transportation is a derived demand, and individuals use transport to maximise opportunities, and will travel further as relative costs fall. Increasing wages and falling motoring costs over the last half century have led to an explosion of private transport use in the UK, with a five-fold increase since 1960. The growth in travel distances is comprehensively private transport based while in

contrast public transport has fallen significantly, though has begun to increase in the last fifteen years.

Energy use and carbon emissions in the transportation sector are a product of travel distances and mode-choice. Policies for sustainable transport are geared towards reducing journey distances and reducing car use in favour of public transport, walking and cycling. A major technological revolution is currently underway in converting automobiles from petroleum based internal-combustion vehicles to electric drive-train vehicles. The environmental impacts of private transport will therefore be curbed through electrical technologies but will remain significant. The relative advantages of public transport, walking and cycling are not expected to change due to these advances.

3.3 Urban Form and Sustainable Travel Relationships: a Review of the Empirical Evidence

The nature of relationships between urban form and travel patterns has been strongly debated in recent geographical and planning research. There is an extensive literature of empirical and statistical studies into these relationships, and this research is summarised in the following sub-sections. Studies vary in scope, with a small number of aggregate metropolitan analyses for the comparison of multiple cities together (Sub-Section 3.3.3), and a much larger body of research investigating relationships within cities at individual survey level and disaggregate intra-urban scales (Sub-Section 3.3.4-3.3.5). Different scales have particular advantages and disadvantages, and highlight particular aspects of the relationships between urban structure and travel patterns.

Regarding the definitions of concepts used throughout this chapter: the term urban form is used interchangeably with the built-environment to describe physical properties of cities; land use refers to the spatial distribution of socio-economic functions; and accessibility describes the potential for accessing facilities by various transport modes. Ambiguities in these concepts arise from their close spatial integration in urban contexts as discussed throughout this chapter.

3.3.1 The Theoretical Basis of Urban Form and Travel Relationships

The proposition that urban form influences travel depends on processes that link individual travel behaviour to the spatial structure of the city. The main channel by which urban factors affect travel behaviour is likely to be through influencing accessibility, in terms of affecting the connectivity and distances/costs between trip origins and destinations. Thus in compact city type planning policies it is argued that high densities and fine grained mix-of-uses reduce travel distances, make public transport and walking more feasible, whilst being associated with reduced automobile accessibility (Jenks *et al.*, 1996). Urban form measures (such as density and mix-of-uses) have been argued to be proxies for accessibility and generalised cost factors (Handy, 1996), and therefore influence travel behaviour in so much as they change accessibility.

There are of course a great many other factors that affect accessibility, such as financial costs (related to taxation policy and income), car ownership, public transport services, congestion, planning policy and transportation technology, amongst many others. Transportation systems and land uses dynamically interact and evolve over time as discussed in Chapter 1. These multivariate and dynamic interrelationships greatly complicate the study of urban form and travel patterns, and lead to difficulties in the analysis of causality (discussed in the next sub-section). The three main types of trip property analysed are trip generation, trip distribution and mode-choice (corresponding to the first three stages of the four stage transport model introduced in Section 2.2). Trip generation is largely a product of socio-economic factors (Ewing and Cervero, 2001), including household size and structure (e.g. families with children generally require more travel), employment characteristics and income, so it is the latter two processes of trip distribution and mode-choice that are largely the focus of urban sustainability studies. These are highly interdependent, with trip origins and destinations being a product of long term residential, workplace and school location decisions as well as shorter term social, leisure and shopping trip decisions and routines. Both locational and travel decisions depend on the opportunities available (housing, jobs, facilities etc.), and these are in turn connected to accessibility, land use and urban form. An important decision for households is car ownership which has clear long term effects on travel behaviour (discussed in Sub-Section 3.3.4).

As well as being considered part of long term locational and car ownership decision making, mode-choice can also be analysed in relation to specific journeys where trip origins and destinations are known. In this context mode-choice depends on the absolute and relative costs of available travel modes, mainly in terms of time and money, as well as additional softer factors such as individual preferences, comfort and safety. Individual modes compete against each other for patronage. There is an established theory and evidence base exploring mode-choice from the perspective of consumer theory and discrete choice modelling (Ben-Akiva and Lerman, 1985). The idea of achieving a *mode-shift* to more sustainable travel pattern involves changing the relative costs of travel between modes, either by improving accessibility by non-

97

motorised and public transport modes, and/or by reducing accessibility by car or increasing the costs of car ownership.

From a policy perspective, it is not straightforward to use urban form measures to change mode-choice or trip distribution to more sustainable patterns due to the slow, incremental, capital-intensive nature of the built-environment. Other policies are likely to have more immediate short term effects, such as fuel taxation rises (Gordon, 2008). On the other hand the long-term path-dependent nature of urban development tends to physically fix accessibility relationships, and the built-environment can have very long term impacts on travel patterns that are difficult to alter (see Chapter 1). Furthermore achieving sustainable travel patterns is highly likely to depend on achieving synergies between fiscal, public transport and built-environment planning policies.

In summary urban form is linked to travel behaviour through connections to accessibility, which can influence residential and workplace location decisions, as well as mode-choice. Many other factors also affect travel costs, and factors such as car ownership, household structure and fuel costs are likely to have more direct and influential relationships with travel patterns compared to urban form variables. The path dependent nature of the built-environment means however that urban form and transportation infrastructure can have important long term relationships with travel patterns.

3.3.2   Methodological Issues in the Analysis of Urban Form and Travel Patterns

As discussed above, a great many factors influence urban travel patterns, and these factors are dynamically interrelated. So the challenge becomes one of analysing these multiple factors together using multivariate models. There are a number of methodological issues to consider for this task. Here we discuss the importance of socio-economic factors in analyses, choices in which variables to use, and the effect of scale and disaggregation decisions.

An important question to test is the degree to which socio-economic attributes influence travel behaviour. Socio-economic variables include income,

household composition, age, employment and so forth. These socio-economic factors have significant relationships with residential location (as well as car ownership) and therefore multi-collinearities with built-environment variables are likely to occur. These correlations apply at a range of scales, from the metropolitan scale (where cities vary in their levels of prosperity, car ownership and fiscal policies) and to intra-urban studies, where housing market processes lead to the clustering of socio-economic groups in particular areas of the city. For example in the UK context the suburbs are typically areas of relatively high incomes, families with dependent children, elderly households, and so forth. City centre populations include more single people, are generally younger and are often lower income. In Sub-Sections 3.2.3 and 3.2.4 the degree to which socio-economic variables are incorporated in existing research is considered.

A second important issue is to determine which of the various urban form, land use and/or accessibility measures are to be included in studies. This is complicated by correlations between these various factors. As discussed above, it has been argued that built-environment variables are essentially proxies for accessibility, and therefore the inclusion of accessibility factors should reduce or remove the influence of built-environment variables. This is not straightforward to achieve however, due to difficulties in the measurement and understanding of accessibility. Accessibility is a relatively abstract concept that is not directly controlled by planners and subsequently has been less commonly analysed. Much of the literature is based on physical planning variables such as density, land use and urban design factors such as street layouts. This is discussed further in Sub-Section 3.3.4.

In addition to complications regarding built-environment variables, there are similar complications with which travel behaviour variables to measure. Disaggregate studies often focus on particular trip purposes, or on a particular aspect of travel behaviour such as travel distances and mode-choice. This enables more focussed analyses and detailed explanations of particular travel behaviour relationships. The challenge however for narrowly focussed studies is that, from a sustainable planning perspective, all trip purposes and all travel decisions affect energy use and carbon emissions. Therefore multiple studies

that focus on different cities and different aspects of travel behaviour need to be integrated together for a comprehensive analysis of travel patterns.

The final issue to consider is the scale and disaggregation of studies. Studies range from macro level metropolitan-wide aggregate analysis, to meso level spatial zones of various sizes, and finally micro level individual level studies. Results will vary depending of the scale of analysis, a geographical phenomenon known as the Modifiable Areal Unit Problem (see Section 4.1). Individual level surveys are advantageous for including detailed socio-economic information and travel behaviour information. The level of detail does however generally restrict sample size, and may lead to sampling errors (where evidence from the sample is misrepresentative of trends in other areas). Sampling error issues are also relevant at the metropolitan scale, where trends in particular cities may be misrepresentative of broader national and international pictures. Much of the literature assessing sustainable urban form relates to North America, and a degree of caution has to be taken in applying these results to a UK context.

Intra-urban studies can also be carried out at the level of districts and neighbourhoods using comprehensive sample data as census information. This approach has the advantage of greater metropolitan coverage than individual surveys allowing the analysis of city-wide trends. On the other hand it is much more problematic to include individual level detailed socio-economic and travel information, and there is the risk of ecological fallacy errors, where neighbourhood level characteristics are assumed to apply to all individuals within that neighbourhood.

3.3.3   International City Comparisons of Urban Form and Transportation Energy Use

International studies provide a means of comparing city trends at a global scale, and of benchmarking cities against their international peers. As environmental impacts are global it is important to include a global perspective in sustainability studies. The scope of such studies presents considerable

challenges in data collection and analysis due to high international diversity in socio-economic, political and physical urban dimensions.

Much of the research debate (particularly in the 1990's) centred on the link between density and travel- the basic argument being that higher densities result in the more efficient use of land, reduced travel distances, greater public transport use, and generally enable a greater intensity and diversity of activity (Banister, 2005; Jenks *et al.*, 1996). Higher densities could increase the potential for local services, amenities and contacts, and facilitate non-motorised travel. As well as supporting public transport by increasing the population within walking distances of services, high densities are also likely to be related to slower more congested car travel. These pro-density arguments were made by Newman and Kenworthy (1989; 1999) based on the evidence of a large scale data gathering exercise for a selection of world cities. Their research identified a strong inverse correlation between transportation energy use[1] and metropolitan residential densities as shown in Figure 3.13. Distinct groups are visible in the graph largely corresponding to US, Australian, European and Asian cities, with US cities having the highest transportation energy use. Similar inverse correlations between density and transport energy use have also been found in studies of UK cities (ECOTEC, 1993). The magnitude of the international variation in transportation energy use is striking in Figure 3.13, and this was an important finding from the study, particularly as there is a lack of similarly broad international research. Their pro-density interpretation has however provoked many critical responses (Gomez-Ibanez, 1991; Gordon and Richardson, 1996). As discussed in the previous sections, travel patterns result from a variety of interrelated socio-economic, built-environment and travel behaviour factors that co-evolve together. Therefore multi-variate analysis is necessary to assess the importance of density in relation to these other factors.

---

[1] The original Newman and Kenworthy study (1989) measured transportation energy use in terms of road based private gasoline and diesel consumption. The updated 1999 study added estimates of public transport energy use to this figure.
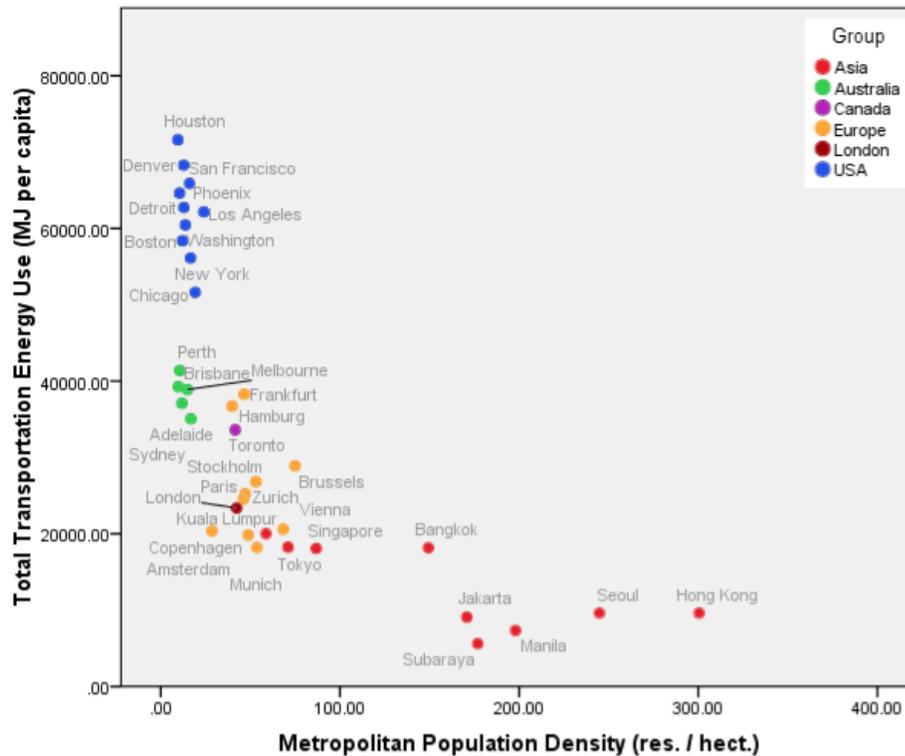
Figure 3.13: Graph of Private Transportation Energy Use Per Capita versus Metropolitan Residential Density 1990. Data source: Newman and Kenworthy (1999).

For this analysis we have used the dataset produced by Newman and Kenworthy (1999), henceforward referred to as *NK1990*, which is a 1990 update of their earlier 1980 study (Newman and Kenworthy, 1989), henceforward referred to as *NK1980*. This is a rich resource in terms of its international coverage, though some caution must be taken due to differences in city boundary definitions and probable variations in measurement accuracies between city datasets. A sub-sample of cities is used for this review[1], with twenty-nine cities from North

---

[1] There are several issues that result from the inclusion of some Asian cities in the same analysis as the other groups, due to much lower incomes in some less developed Asian countries, strict planning regimes in ex-communist states and dramatically different cultures of high density living. Hong Kong for example has six times the residential density of London. It has been argued that these extreme examples skew the analysis (Mindali *et al*. 2004). Therefore low income cities (Jakarta, Manila, Subaraya, Bangkok, Kuala Lumpur) and the extremely high density cities (Hong Kong, Seoul) have been excluded for this review.

America, Australia, Europe and Asia. The city sample is weighted towards fairly large cities from the core economies of the developed world. The most recent data for 1990 (now unfortunately two decades old) is used in the analysis. The full dataset is provided in Appendix A.

We now discuss the analysis of urban form and travel patterns, using examples from *NK1990*. One of the most substantive critiques of the pro-density viewpoint is that analyses have failed to consider socio-economic variation, principally income and fuel prices (Gomez-Ibanez, 1991), which are key influences on travel behaviour (Gordon, 2008; Stead, 2001). These factors are now discussed in turn. Travel distances generally increase as incomes rise (and car ownership increases), and thus income variation between cities is likely to have a significant effect on travel patterns. We can include aggregate income in the analysis of density by taking the ratio of transportation energy use against the gross regional product for city metropolitan areas, illustrated in Figure 3.14. When the relationship with residential density is graphed again, this time using the energy/income ratio, the same general relationships exist, dividing European and US cities, though the magnitude of the variation has been reduced. Lower income Australian cities are grouped with the US cities.

Fuel taxation represents a significant policy divide between North American and European cities, with petrol prices in Europe between two-and-a-half to three times more expensive than in the USA (Metschies, 2005). A very basic measure including fuel prices in the analysis is shown in Figure 3.15 where a gasoline purchasing power indicator has been calculated by dividing metropolitan Gross Regional Product per capita by national gasoline prices in 1993 (1990 data was unavailable for all the study cities). By again graphing the transportation energy use ratio (this time using gasoline purchasing power) against residential density, we can see that the correlation has become significantly weaker and that many US cities score better than their European counterparts using this measure. The graph in Figure 3.14 implies that the density-energy relationship is largely dependent on a density-fuel taxation relationship, and indeed multivariate regression analysis of Newman and

Kenworthy's 1980 data has found fuel costs to be the principal factor in explaining variations in energy use (Kirwan, 1992).
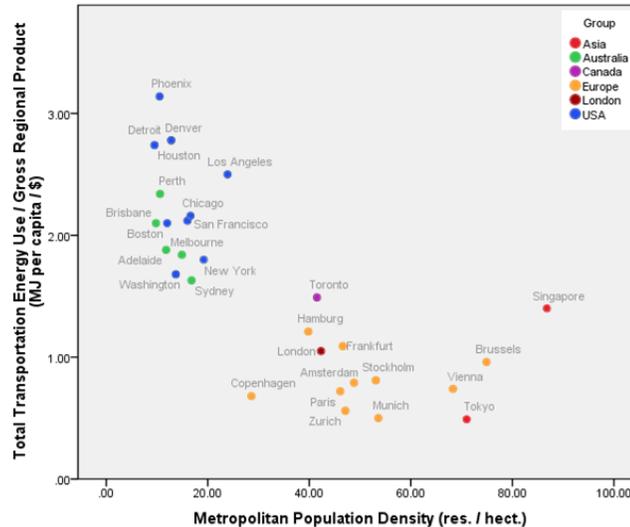
Figure 3.14: Graph of Private Transportation Energy Use Per Capita / Gross Regional Product, versus Metropolitan Residential Density 1990. Data source: Newman and Kenworthy (1999).
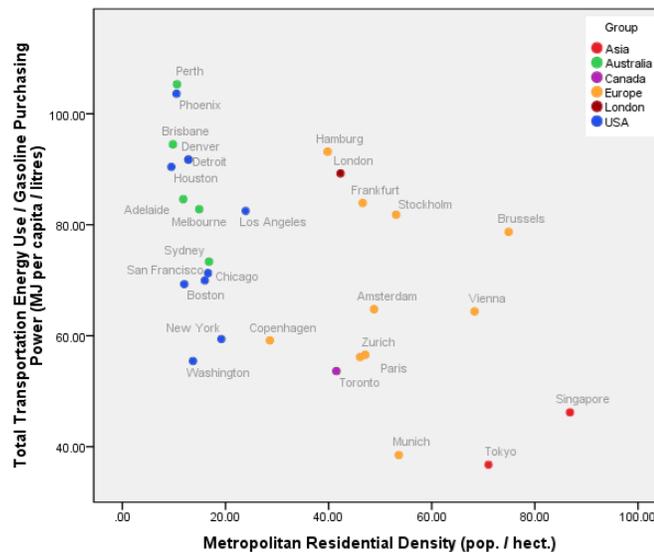
Figure 3.15: Graph of Private Transportation Energy Use Per Capita / Gasoline Purchasing Power (Income / Gasoline Cost 1993), against Metropolitan Residential Density 1990. Data sources: Newman and Kenworthy (1999); Metschies (2005).

Studies of the influence of fuel prices on car travel in the UK have found demand to be responsive to price increases, with elasticities in respect to fuel use of around -0.28 in the short term (Goodwin, 1992), i.e. a 10% increase in fuel costs would be expected to produce a 2.8% decline in fuel consumption.

Furthermore long term elasticities are considerably higher, estimated at -0.77 (*ibid*.). This is due to long term interactions between prices, travel behaviour, car ownership, location decisions and the built-environment (Gordon, 2008). Thus from this perspective fuel prices have a highly significant causal role in guiding travel behaviour.

This conclusion questions whether density and urban form more generally are of importance in influencing travel patterns, or at least whether density has any causal role. On the other hand, in support of the pro-urban form viewpoint, significant travel variation can be seen in the dataset independent of fuel costs and incomes. The large variation in transportation energy use between cities within nation states, for example between the US cities of Washington and Phoenix and the German cities of Munich and Hamburg, cannot be explained by fuel price or income variation. Similarly Toronto uses nearly 40% less energy than the most efficient US cities, and has only marginally higher fuel costs.

Modelling the dynamic relationships between fuel prices and urban form is beyond the scope of this research. An alternative approach is to consider European or North American cities in isolation, as these groups are considerably more homogenous in terms of fuel costs. We focus here on the European context. Figures 3.16 and 3.17 graph density relationships for European cities against private transport distance per capita. It has been argued no correlation with density exists amongst European cities (Gordon, 2008), yet in this analysis there is a weak inverse correlation with metropolitan population density, and a moderately strong inverse correlation with inner-city population density. The larger size of London and Paris suppresses car travel, and so these cities sit below the main trends. Note that private transport distance has been chosen rather than total transport energy, as the latter does not include non-motorised travel. The presence of high levels of cycling in cities such as Amsterdam and Copenhagen appears to be independent of any urban form measures recorded in *NK1990*. This weakens correlations between transportation energy use and density for European cities. Overall there do appear to be relationships between density and car travel in European cities independent of fuel costs using the measure of inner-city density.
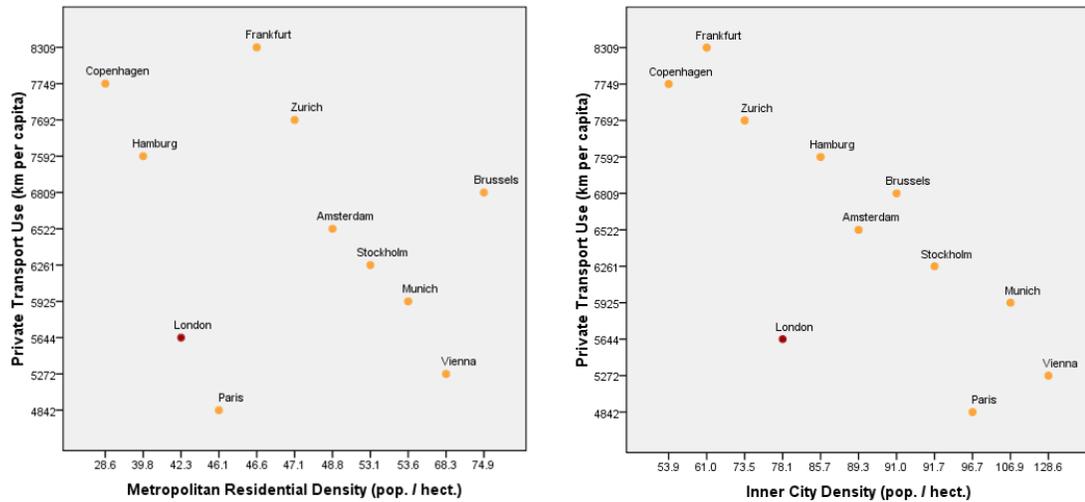
Figure 3.16 & 3.17: Graphs of Metropolitan Residential Density (left) and Inner-City Density (right) against Distance Travelled by Motorised Private Transport.
Data source: Newman and Kenworthy (1999).

A range of other urban form and transportation attributes are recorded in the *NK1990* dataset, including employment centrality and transportation infrastructure. In the following discussion these are explored for the European group of cities in relation to private transport travel. The distribution of employment is likely to influence travel patterns. One significant aspect of employment geography is centralisation. Generally a high proportion of jobs in the city centre and inner-city relates to a strong radial public transport network. This relationship is not however clearly identifiable for European cities in the *NK1990* dataset, either in terms of inner-city employment density or proportion of jobs within the CBD as shown in Figures 3.17 and 3.18. There are cities such as Amsterdam with relatively low car travel and low employment centralisation, whilst Frankfurt has relatively high car travel at moderately high centralisation. Employment geography has been argued to be a significant factor in affecting travel patterns, but there is a lack of research evidence in this area (Badoe and Miller, 2000; Banister, 2005). It appears basic measures of employment centralisation do not produce strong relationships. More in-depth analyses of employment geography and travel patterns are explored at an intra-metropolitan scale in Chapter 6 of this research thesis.
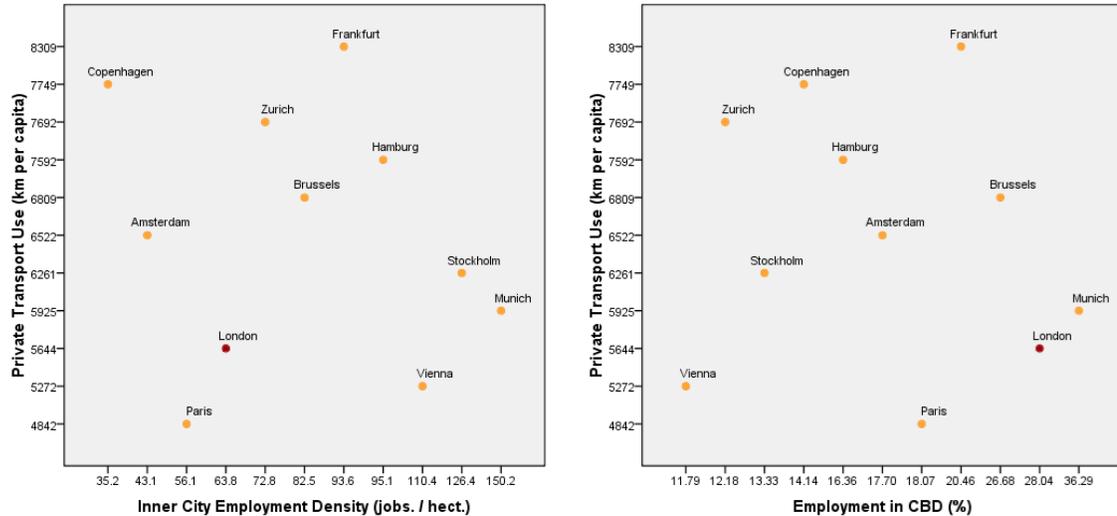
Figure 3.18 & 3.19: Relationships Between Employment Density (left), Employment Centrality (right) and Transportation Energy Use / GRP. Data source: Newman and Kenworthy (1999).

In addition to urban form and land use factors, transportation infrastructure measures can be analysed in relation to travel patterns, such as the supply of road space and public transport services. Positive correlations between car travel and road supply/average speed are identifiable in *NK1990* as shown in Figures 3.20 and 3.21. This confirms the argument from Section 3.2 that driving distances increase as car accessibility increases. The measures of public transport infrastructure also show interesting relationships with private vehicle travel (Figures 3.22 and 3.23). Where vehicle miles are lower, a greater proportion of trips are taken by public transport. There is not however such a simple relationship with public transport provision as shown in Figure 3.23. Similarly public transport speed is also not strongly correlated with car travel in the *NK1990* dataset. Public transport use is likely to depend on relative accessibility (including financial cost) versus car travel and physical urban structure, which is not necessarily the same as the absolute level of public transport service. Overall the transportation infrastructure variables show that travel patterns between cities are closely related to transportation supply, and thus likely accessibility, in terms of infrastructure and government policies and investments. This conclusion is likely to also apply to walking and cycling, although a lack of data prevents testing this relationship.
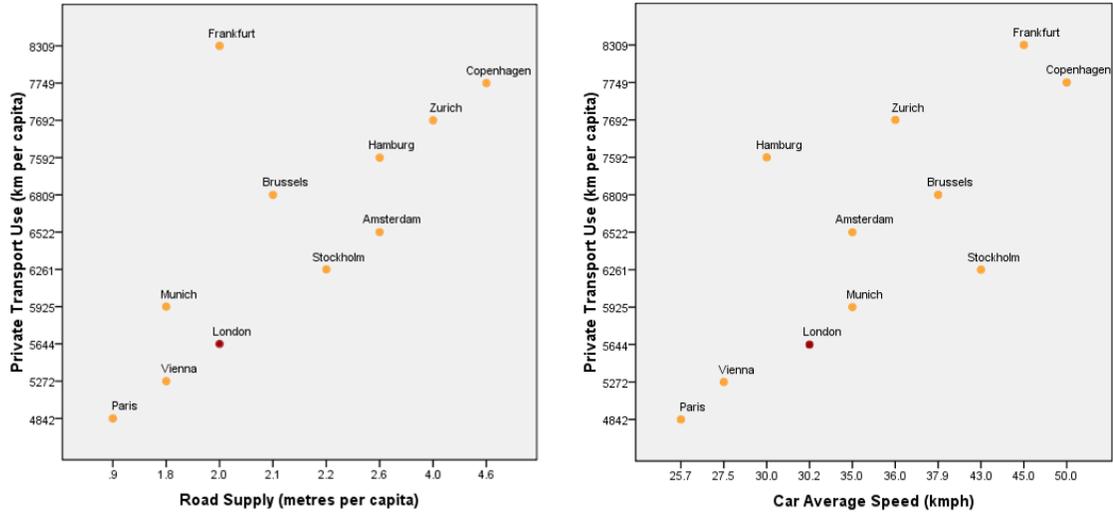
Figure 3.20 & 3.21: Graphs Comparing Average Speed by Car (left) and Road Supply (right) with Transportation Energy/Income Ratio. Data source: Newman and Kenworthy (1999).
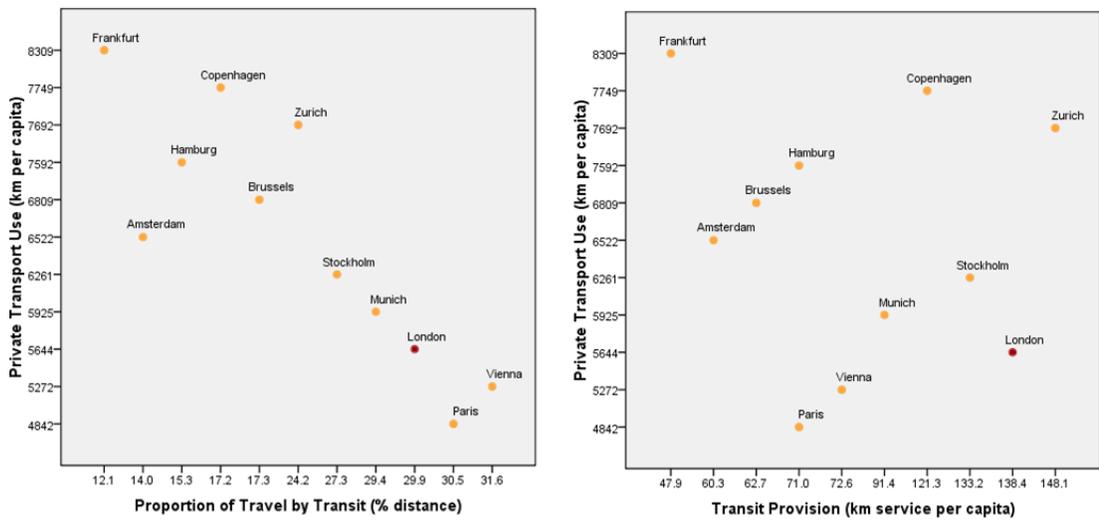
Figure 3.22 & 3.23: Graphs Comparing Passenger km on Transit (left) and Transit Supply (right) with Transportation Energy/Income Ratio. Data source: Newman and Kenworthy (1999).

In conclusion to the analysis of the *NK1990* dataset, there are inverse correlations between density measures and transportation energy use, but these are interwoven with complex cross-correlations with fuel taxation, road transport provision, public transport provision and cultures of non-motorised transport. Fuel taxation in particular is the most significant factor in explaining

108

international variation, and is closely correlated with density. Urban transportation energy use is therefore a product of interrelated economic, social, infrastructural and urban form factors, as illustrated in Figure 3.24[1]. Based on travel pattern, infrastructure, urban form and taxation measures we can group the cities in *NK1990* into general categories, such as full-motorisation dispersed cities (e.g. Houston, Los Angeles); high motorisation cities (e.g. Chicago, Sydney); strong transit cities (e.g. Paris, London); strong active travel and transit cities (e.g. Copenhagen, Zurich), and super-dense full transit cities (e.g. Hong Kong, Tokyo). Note that this perspective has much in common with the transportation archetypes view introduced in Chapter 1, where the history of growth and network logics of transportation modes strongly influences their urban evolution.
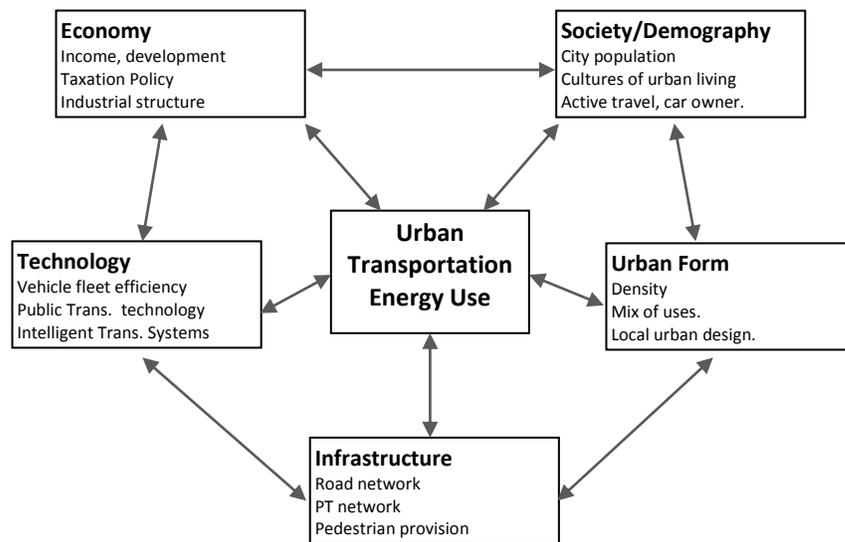
Figure 3.24: Factors Affecting Urban Transportation Energy Use.
Adapted from Newman and Kenworthy (1999).

From an urban planning perspective, the conclusion that transportation energy use depends on multiple economic, social, infrastructural and urban form aspects does not necessarily provide practical guidance for land use policy.

---

[1] Figure 3.24 includes transportation technology factors which were discussed previously in Sub-Section 3.2.3.

Taking a more narrow physical planning view, we can conclude that density is associated with many other factors and is of questionable direct causality in influencing travel patterns. While the most fuel efficient cities have higher metropolitan densities, density is likely to be a 'necessary but not sufficient' condition of greater non-motorised and transit travel. It is possible that more disaggregate density measures would produce stronger correlations (and indeed the following sub-section provides evidence for this point) but overall we require a more sophisticated theoretical approach to explaining travel patterns than the straightforward causality of physical form.

We can return to the earlier point that it is accessibility and travel costs that are the immediate influences on travel distances and mode-choice (and are connected to longer term behaviour such as car ownership and residential location), and that built-environment measures are essentially accessibility proxies (Handy, 1996). Accessibility describes the potential for populations to access facilities based on travel costs (Hansen, 1959), and can incorporate the range of factors discussed in the previous analysis, including fuel tax, infrastructure and built-environment variables. The accessibility perspective corresponds with many patterns in the *NK1990* dataset, such as the strong relationships found between high road transport provision, high vehicle speeds, and high proportions of car travel. It may also help explain why high public transport provision is only weakly related to low car travel, as private vehicle accessibility could be higher in relative to private transport despite good public transport services. Accessibility variables are not modelled explicitly in the *NK1990* dataset. Studies that do include accessibility analysis are discussed in the next section.

Accessibility varies considerably at intra-urban scales, and this highlights the weakness of analysis at aggregate metropolitan scales. The strong correlation between inner-city density and more sustainable travel patterns in the European group implies that increases in density are most significant where they correspond to high public transport accessibility. Detailed intra-urban measures may reveal stronger trends. Spatially disaggregate analysis may also help to shed light on the weak relationships found between employment centrality and

sustainable travel patterns for the European cities group. The mixed results regarding centrality are relevant to this research, as they may indicate the influence of polycentric employment patterns.

3.3.4 Micro-Scale Analysis of Travel Patterns, Accessibility and the Built-Environment

While city comparison studies provide a useful broad overview of urban travel patterns, the approach does not allow the consideration of heterogeneity within cities, or the travel behaviour decisions of individuals. Disaggregate analysis is required to analyse this variation. At a basic level it is clearly apparent that travel patterns vary spatially at intra-urban scales. Suburban residents are typically frequent car users, whilst inner-city populations are more likely to travel by public transport and non-motorised modes. We would expect correlations to exist between intra-urban form and travel patterns. As with the previous section however, the challenge is to explain the complex cross-correlations that exist between built-environment, accessibility and socio-economic variables and highlight the most significant factors in these relationships. Disaggregate studies have the advantage that more detailed measures of urban form, land use and accessibility can be considered, and in micro-level studies socio-economic variables can be controlled for at the level of the individual trip maker. This section discusses micro-scale individual studies and the following section considers meso-scale intra-urban analysis.

The evidence base from disaggregate analysis is extensive, with studies coming to mixed and conflicting conclusions on the importance of urban form in travel behaviour (Badoe and Miller, 2000; Banister, 2005). Studies vary in scales of analysis employed, statistical modelling methods used, the areas of study and the variables included. The latter issue of variable choice is important as the high degree of cross-correlations in urban dimensions can lead to false correlations where significant variables are absent from studies. We mentioned in the previous section the importance of accessibility and socio-economic variables in travel behaviour, and disaggregate analysis presents an opportunity to model these dimensions alongside built-environment variables. An overview of potential variables that could be included is presented in Table 3.4. The

independent variables are classified into socio-economic, urban form/land use, and accessibility/transport supply factors. Accessibility bridges between physical geography and socio-economic perspectives by considering the travel costs for populations of reaching urban facilities. Multivariate modelling that includes these factors can assess their relative significant in influencing travel patterns, and answer key questions such as whether socio-economic factors are the dominant consideration in travel patterns; and whether urban form relationships are a result of accessibility influences.

Table 3.4: Overview of Variable Types in Disaggregate Urban Form -Travel Behaviour Studies.

Independent Variables

1) **Socio-economic**
   a) Demographic
      i) Household structure
      ii) Age
      iii) Gender
      iv) Health / mobility
   b) Private Transport ownership
      i) Driving licence
      ii) Number of cars / car availability
      iii) Cycle availability
   c) Employment
      i) Income
      ii) Employed / unemployed
      iii) Occupation type
   d) Behavioural
      i) Personality type / attitudes
      ii) Cultural factors, trends

2) **Urban Form / Land Use**
   a) Residential/trip origin measures
      i) Density population / floorspace
      ii) Housing type / car parking
   b) Non-residential/trip destination measures
      i) Density employees / floorspace
      ii) Building type / car parking
   c) Land use measures
      i) Function
      ii) Mix-of-uses / diversity / jobs-housing balance
   d) Design
      i) Street layout
      ii) Pedestrian provision, severance etc.
      iii) Cycling provision
      iv) Transit integration

3) **Accessibility / Transport Supply**
   a) Potential measures
      i) Automobile
         (1) Regional accessibility
            (a) Origin access to facilities/opportunities
            (b) Destination access to facilities/opportunities
         (2) Local accessibility / Connectivity
            (a) Origin parking availability/cost
            (b) Destination parking availability/cost
      ii) Transit
         (1) Regional accessibility
            (a) Origin access to facilities/opportunities
            (b) Destination access to facilities/opportunities
         (2) Local accessibility / Connectivity
            (a) Origin access to transit station / services
            (b) Destination access to transit station / services
      iii) Walking / Cycling
         (1) Regional accessibility
            (a) Origin access to facilities/opportunities
            (b) Destination access to facilities/opportunities
         (2) Local accessibility / Connectivity
            (a) Origin access to pedestrian routes, cycle lanes
            (b) Destination access to cycle parking
   b) Journey specific
      i) Generalised cost/ travel time of journeys by available modes.

Dependent Variables

4) **Travel Behaviour**
   a) Work travel / non-work travel / all travel
      i) Trip Frequency
      ii) Distance, Time
      iii) Mode-choice
      iv) Trip chaining
   b) Car Ownership

The dependent travel behaviour variables that models try to predict are a further key variable choice. It is common to analyse frequency, distance and mode-choice separately, either in isolation or through multiple linked models (Ewing and Cervero, 2001). Additionally work travel and non-work travel can be modelled separately. As discussed previously, trip frequencies are generally a product of socio-economic factors, therefore urban form studies generally focus on distance, mode-choice and car ownership as the dependent variables, or combinations of these such as total vehicle miles travelled. The number of independent and dependent variables in Table 3.4 is high, and the list is by no means comprehensive. Research over the last fifteen years has begun to model a more comprehensive range of these variables and control for the most significant factors in travel behaviour (Ewing and Cervero, 2010). A consensus has emerged around a relatively weak, but not insignificant, influence for urban form factors once socio-economic and accessibility factors have been controlled for.

Controlling for socioeconomic factors is required to provide a rigorous methodology for the analysis of the built-environment and travel patterns. Current travel demand modelling methods (e.g. activity based models) have been developed at the disaggregate level of the individual trip-maker to include the diversity of behavioural responses which occur amongst different types of people. Generally the most significant socio-economic factor in influencing travel patterns is car ownership (Banister, 2005; Cervero, 1996b). Car owners invest in their vehicles financially (with purchase costs greatly exceeding running costs in current ownership structures) and to a varying extent behaviourally and psychologically, and therefore make use of their cars once purchased. Non-car owners in contrast are clearly much more restricted in terms of car availability and subsequently use. The decision to own a car is in turn interrelated with residential and workplace location decisions, as well as individual and household socio-economic factors. Households owning fewer cars tend to drive less and use public transport and non-motorised modes more often. One of the simplest means of considering socio-economic factors is to include car ownership as an independent variable. This approach does not attempt to understand the dynamics between car ownership preferences,

residential location and subsequent activity/travel decisions. Alternatively car ownership can be modelled as an endogenous function, linked to other socio-economic factors and to travel patterns (Chen *et al.*, 2008).

The connection between travel preferences and residential location is an important consideration. Populations to an extent choose housing locations based on the lifestyles they wish to lead (Kitamura *et al.*, 1997), and travel patterns are a component of these lifestyles. Therefore it is possible for relationships between urban form and travel behaviour to work both ways: i.e. populations do not necessarily choose to travel a certain way because of where they live, they can choose where to live depending on how they want to travel (a process known as residential self-selection). Therefore personal attitudes towards lifestyles acting through residential location can lead to correlations between urban form and travel patterns. While it is possible to include socio-economic variables in micro-level studies to control for such effects, more behavioural and attitudinal aspects that can effect travel patterns are rarely included in built-environment studies (Kitamura *et al.*, 1997). Some caution must be taken on this issue however as it is possible for the importance of personal attitudes to be overstated. Two-way relationships between attitudes and behaviour are clearly part of human nature. The international comparison discussion in Section 3.3.3 clearly illustrates shared *city-wide* urban cultures are shaping individual attitudes towards transport modes, as for example in the cycling cities of Copenhagen and Amsterdam.

After controlling for socio-economic considerations, studies can then gauge the influence of accessibility and urban form factors. The following discussion considers the various accessibility and urban form measures that are possible. Accessibility describes the opportunities available to a population in a specific location depending on travel cost. As discussed previously, it has been argued that the built-environment influences travel patterns by influencing accessibility. If this is the case, then studies that include both accessibility and

built-environment variables should find a significant role for accessibility variables, and low or insignificant relationship for built-environment variables[1]. Accessibility measures can be classified as general potential measures, which consider opportunities to a range of populations/facilities depending on travel cost, or alternatively can be journey specific measures, which consider the travel costs of a particular journey (typically by several modes). The latter type relates only to studies where the origin and destination of a trip is known and is used for mode-choice modelling.

Accessibility measures can be calculated from the perspective of trip origins (typically residences) and trip destinations (typically activity/employment centres). This distinction also applies to urban form and land use measures. Badoe and Miller (2000) note that there is a strong tendency in theory and practice to focus on the residential side of land-use transportation relationships, while the trip-end side may have a more direct relationship with travel behaviour and furthermore be more susceptible to successful planning measures. The preoccupation of the transit-orientated sustainability literature with residential density and neighbourhood design may then be limited if the trip destination context is more significant (Ewing and Cervero, 2001).

The scope of accessibility measures can vary depending on trip purposes and modes. The distinction between regional and local accessibility measures is one means of defining scope (Handy, 1993). Regional accessibility covers the activity space of common medium distance journeys such as commuting, comparison shopping and leisure activities; while local accessibility refers to facilities accessible within walking distances. Local accessibility measures are essentially connectivity measures, for example a measure of local accessibility to public transport services is a measure of transit connectivity, and can be

---

[1] Note it is not always straightforward to differentiate accessibility and built-environment measures. For instance street network design measures essentially consider both physical structure and pedestrian accessibility simultaneously.

considered for both trip origins and destinations. Regional accessibility relates to the position of a residential district in relation to accessing major employment, population and services centres. An example of a regional accessibility measure is *jobs within 45 minutes travel time*. Where detailed accessibility data is unavailable, proxies are often used such as distance to the city centre (the calculation of more accurate network accessibility measures is discussed in Section 4.7). Regional accessibility is considered to be the most important geographical factor for car owners on total vehicle miles travelled (Ewing and Cervero, 2010). Effectively this conclusion follows the common sense logic that residents in more remote locations need to travel further to access facilities. This conclusion indicates that focussing on local design without considering the regional context is a flawed approach to sustainable travel planning. Additionally parallels can be drawn with studies that show the decline in vehicle miles as settlement sizes increase (ECOTEC, 1993), as larger settlements support a greater scale of services and thus have higher regional accessibility. Local accessibility can also have a more modest impact on travel distances, by reducing trip lengths for purposes such as convenience shopping (Handy, 1995).

Once socio-economic and accessibility variables have been included, then the influence of urban form variables independent of these factors can be assessed. There are a range of built-environment measures that can be used, including density (both of residents, employees, and built form), land use mixes and street design. (Note there are a wide range of spatial analysis issues that occur in the measurement of these variables as discussed in Section 4.4). There is no universal consensus on the importance of these variables on travel patterns, though some trends are evident from the comparison of studies. Residential density has been a focus of sustainable travel studies following Newman and Kenworthy's (1989) research and debates around compact city policies. The empirical evidence at disaggregate levels is very mixed. A number of studies have found an association with higher densities and more sustainable mode-choices (Cervero, 1996b; Frank and Pivo, 1994) but generally these studies have not fully accounted for socio-economic and accessibility factors. The role of residential density as a direct explanatory variable has been found to be

marginal in many studies once other socio-economic and accessibility factors are accounted for (Badoe and Miller, 2000; Ewing and Cervero, 2010). Densities can also be measured at trip destinations, typically in the form of employment densities for workplaces. It has been argued that findings show that increased employment concentrations have significant impacts on more sustainable mode-choice (Badoe and Miller, 2000). On the other hand, it is likely that destination-based accessibility measures will also account for much of this variation. Additionally one of the most important factors in determining private vehicle accessibility is car parking cost and availability. This is seldom modelled as it is likely to be closely connected to destination density.

One means of quantifying the relative importance of the many variables is to calculate elasticities from multivariate modes. These describe how the dependent variable in the model would respond to a 1% change in the independent variable. Ewing and Cervero (2010) conducted a meta-analysis combining many research studies of the influence of the built-environment on vehicle miles travelled as shown in Table 3.5. The results point to regional accessibility variables (job accessibility by auto and distance to downtown) having the strongest elasticities. The relatively high values for land use mix and street network measures also indicate that local accessibility could play an important role. The values for density measures are notably low. The meta-analysis approach is a useful means of summarising relationships. There are some shortcomings as significant variation in elasticity values exists between the studies used to form the weighted averages. Furthermore the number of studies using advanced residential self-selection techniques is low and the elasticity approach cannot capture the potential synergistic and non-linear relationships that potentially exist in travel pattern relationships.

The analysis of mode-choice rather than vehicle miles travelled can produce somewhat different results than analyses of total vehicles miles. A recent study by Chen *et al*. (2008) of commuting mode-choice in New York, notable for including a range of accessibility measures and controlling for self-selection, found several built-environment and accessibility variables were significant in predicting private vehicle commuting, including employment density at work,

connectivity to transit at both home and work, job accessibility at work by transit and commute travel time and cost. It is likely the importance of workplace density is connected to car parking availability/cost, which was not included in the study (Chen *et al.*, 2008).

Table 3.5: Weighted Average Elasticities of VMT with Respect to Built-Environment Variables. Source: Ewing and Cervero (2010).

		Total number of studies	Number of studies with controls for self-selection	Weighted average elasticity of VMT (*e*)
Density	Population density	9	1	-0.04
	Job density	6	1	0.00
Diversity	Land use mix (entropy index)	10	0	-0.09
	Jobs-housing balance	4	0	-0.02
Design	Intersection/street density	6	0	-0.12
	% 4 way intersections	3	1	-0.12
Accessibility (origin)	Job accessibility by auto	5	0	-0.20
	Job accessibility by transit	3	0	-0.05
	Distance to downtown	3	1	-0.22
	Distance to nearest transit stop	6	1	-0.05

Overall, it is clear that while relationships between the built-environment and travel patterns are complex and an ongoing research area, a more in-depth understanding of relationships is possible with micro-scale analysis. This research summary indicates that socio-economic variables, in particular acting through car ownership and residential location, are major drivers of travel demand. Of the built-environment related factors, it is accessibility measures that have been found to have the strongest relationships. Regional accessibility has a significant influence on total vehicle miles travelled, while high local accessibility through mix-of-uses and pedestrian focussed streets can also have an impact on travel distances. Correlations with density are largely a product of accessibility factors. For mode-choice analysis, accessibility factors at the trip end may be more significant than trip origin measures. This includes transit connectivity measures and employment density, which is related to car parking costs. Overall both a regional and a local perspective is required to encourage sustainable travel patterns, considering trip origins and destinations and the connections between localities and their regional context.

3.3.5   Meso-Scale Analysis of Journey-to-Work Patterns

The micro-scale analysis discussed in the previous section provides an insightful evidence base for understanding the factors that influence travel behaviour. In the context of strategic urban planning, the key factors identified, such as regional accessibility and socio-economic variables, need to be measured and analysed in the context of specific cities to be used for planning policy. As there is widespread variation within cities in socio-economic geography and accessibility, it follows that intra-urban variation in travel patterns will also be high. This is of importance to urban planners but is not directly tackled in the micro and macro scale approaches. There is a strong case for intermediate 'meso-scale' analyses to allow the study of direct relationships between travel patterns and the intra-metropolitan geography of city-regions. Several studies have taken this approach (e.g. Cervero and Wu 1997; Wang 2000) and there is considerable scope for more research in this area, particularly in a UK context. The meso-scale of analysis is directly relevant to debates over the efficiency of monocentric and polycentric structures.

The characteristics of meso-scale intra-urban city-region analyses are distinct from the micro and macro approaches. There is the potential to achieve more comprehensive sample sizes compared to micro-studies using national survey data such as censuses and travel surveys. The trade-off is that a level of spatial aggregation is necessary (discussed in detail in Section 4.1). The inclusion of socio-economic factors is more practical than macro-scale studies, though remains problematic as there is the risk of ecological fallacy errors[1]. The detailed data requirements of the meso-scale approach have overwhelmingly restricted studies to the analysis of journey-to-work. This is the most data-rich trip type due to its inclusion in national censuses. While commuting remains a significant journey purpose in terms of its economic importance and contribution to congestion (see Sub-Section 3.2.4), overlooking other trip

---

[1] Where aggregate neighbourhood level characteristics are assumed to apply to all individuals within that neighbourhood- see Sub-Section 4.1.3.

purposes is a limitation, as all trip types are relevant to sustainability and transportation efficiency issues.

We focus here on research that has considered how the efficiency and sustainability of commuting patterns has changed over time, particularly in relation to employment and population decentralisation. The main question is whether the decentralisation leads to a better integration of residential and workplace locations, minimising trip distances and facilitating more sustainable modes; or whether decentralisation leads to a disintegration of journey-to-work patterns with less sustainable patterns. A useful diagram of conceptual trip patterns in relation to decentralisation is shown in Figure 3.25 from research by Ma and Banister (2007). In this framework the monocentric city can decentralise into a spectrum of polycentric and hybrid forms. The two opposing polycentric forms are the 'city village' structure with local travel patterns to dispersed centres, and the 'random movement' city with long distance cross-commuting between dispersed centres.

Notes:

In the figure, four different trip patterns within a metropolitan area are taken from Bertaud (2002). Bertaud described:

city (a) as the monocentric model;
city (b) as the urban-village polycentric model;
city (c) as the random-movement polycentric model;
and city (d) as the radial and random movement hybrid model.

Figure 3.25: Conceptual Models of Urban Spatial Structure and Travel Patterns. Source: Ma and Banister (2007).

An early strand of research into regional travel variation comes from Thomas (1969) who studied London's New Towns, developing a self-containment indicator which is still used in current research. An example from the Polynet study (Hall and Pain, 2006) is shown in Figure 3.26. This indicator summarises the degree to which travel is contained within urban settlements. In Figure 3.26

the proportion of live-work residents increases with distance from Greater London. Whilst it is useful to highlight self-containment relationships, this indicator cannot provide detailed sustainability analysis as it omits mode-choice data and simplifies trip distance information. Instead we need to look at data relevant to the dependent variables from the previous micro and macro scale travel studies, such as trip distance, mode-choice and energy use.

Figure 3.26: Self-Containment Measure for Urban Settlements in the Greater South East. Source: Hall and Pain (2006).

Frost and Spence (2008) researched changes in commuting energy use in the major UK cities of London, Birmingham and Manchester using 1981-2001 census data. There have been a number of studies calculating transportation energy using trip length and mode coefficient data (Banister *et al.*, 1997). The Frost and Spence results identified a 25.8% increase in journey-to-work per-capita energy use in London during the 1981-2001, related to increasing distances and greater car use. This figure of 25% is, in the context of twenty years of major socio-economic change, not overly high, and this result is likely connected to the growth of London's urban core during this period (explored in Chapter 5). Birmingham and Manchester, which experienced population decline and counter-urbanisation during this period, were identified as having much

higher per-capita commuting energy increases of 66.2% and 67.2% respectively (Frost and Spence, 2008). This research thesis seeks to extend the Frost and Spence work to consider the underlying intra-urban patterns that generate these city-wide trends. Many more specific land use planning questions (such as how Inner London compares to Outer London; how new employment centres compare to older centres; or what is occurring in wider region beyond the Greater London boundary) cannot be answered using a city-scale methodology, as they require intra-urban scales of analysis. A relevant study incorporating elements of the intra-urban approach comes from Titheridge and Hall (2006), which focuses on journey-to-work patterns for two rail corridors in South East England connected to Greater London. Whilst not including the entire city-region as advocated here, the study is notable for analysing socio-economic variables at an intra-urban city-region scale, and connecting occupational class to mode-choice and travel distance behaviours.

Studies from the US regarding decentralisation and commuting efficiency are highly mixed in their results. Several studies have identified quicker journey times associated with greater decentralisation (Cervero and Wu, 1997; Gordon *et al.*, 1991). This travel time gain does not however necessarily mean sustainability gains, as decentralisation has been linked to mode-shifts away from public transport towards private vehicles on less congested routes (Cervero and Wu, 1997). This is consistent with the conclusions emphasising accessibility in the micro and micro travel pattern analysis, as public transport accessibility will decline outside of city centres. The importance of accessibility was also highlighted by Wang (2000) who identified strong relationships between regional employment accessibility and commuting distances in Chicago. These studies are also significant in considering variation within cities, with intra-urban employment centres in San Francisco (Cervero and Wu, 1997) and Chicago (Wang, 2000) distinct in terms of trip distances and mode-choice. Cervero and Wu also used employment class data to disaggregate their model, illustrating how socio-economic data can be included at meso-scales.

In summary, intra-urban meso-scale analysis provides a useful city-specific geographical approach to analysing travel patterns that complements the micro

and macro scale approaches. Similar accessibility, built-environment and socio-economic relationships are likely to hold at these intermediate scales, although the number of studies is relatively limited and there is significant scope for expanding the intra-urban evidence base. There is great potential to add improved socio-economic and accessibility analysis into the study of commuting efficiency, and advance the analysis of environmental indictors such as energy use and carbon emissions.

3.3.6 Summary

The varied scales of analysis in sustainable urban travel research provide different perspectives on relationships with urban form and are ultimately complementary in building a more complete picture of this complex topic. International comparison studies reveal massive variation in the performance of cities across the world, whilst micro-studies provide evidence on the factors affecting individual travel behaviour. There are significant connections in the research evidence, with cross correlations between socio-economic, urban form/land use and accessibility/infrastructure variables present in both micro and macro scale studies.

Socio-economic factors have strong connections to trip distances and mode-choice. At macro city scales this is this expressed through income and fuel taxation variables, with fuel price being amongst the most strongly correlated variables in the Newman and Kenworthy dataset. At micro-scales the socio-economic variables of car ownership, income and household structure are connected to trip patterns, with car ownership typically the most strongly correlated variable in predicting transport energy use. The influence of socio-economic factors does not negate the importance of planning- there is considerable variation beyond these socio-economic variables. Furthermore planners can influence key factors that affect car ownership. Yet the presence of multi-collinearities with socio-economic factors greatly complicates the identification of relationships between travel patterns and urban form.

We have supported the theoretical argument in this section that accessibility is the key geographical factor on travel patterns and that built-environment

measures, such as density, are essentially accessibility proxies (Handy, 1996). This argument has largely been confirmed in the research review. Whilst accessibility was not modelled directly in the macro-scale analysis, the multiple correlations with density and transportation infrastructure variables support the accessibility perspective, as to an extent does the influence of fuel taxation. In micro-scale studies accessibility variables were modelled explicitly, and regional accessibility was found to be the most significant variable in predicting total vehicle miles travelled in multivariate models, and local accessibility variables were also significant. Whilst density is likely not to have a causal role in determining travel patterns, it is strongly connected to accessibility and relatively high built-environment densities are likely to be a necessary, but not sufficient, condition of greater non-motorised and transit travel. Furthermore some researchers have argued for an additional role of density beyond its influence on accessibility (Chen *et al.*, 2008), and this is likely connected to car parking availability.

Finally we have considered studies at an intra-urban 'meso-scale', which provides an intermediate city-region analysis for strategic planning most relevant to the polycentric focus of this research. The conclusions of the micro-scale analysis- that both local and regional accessibility need to be considered and that trip-end factors are influential- can be further explored at city-region scales of analysis. Existing research at this scale points to similar accessibility and socio-economic relationships, but the number of studies is relatively limited, particularly for the UK, and there is significant scope for expanding the intra-urban evidence base. There is great potential to add improved socio-economic and accessibility analysis into the study of commuting efficiency, and advance the analysis of environmental indictors such as energy use and carbon emissions.

3.4 Policy Perspectives on Sustainable Urban Travel

The previous section considered empirical analyses of relationships between urban travel patterns and spatial structure. This research thesis follows the empirical approach, yet it is necessary to consider the policy context of sustainable travel measures, as the practicality of sustainable travel policies is a vital perspective if any real world changes in urban function are to be achieved. This section provides a brief overview of feasibility issues in sustainability and the range of policy options available to planners.

3.4.1 Socio-Economic Feasibility of Sustainable Travel Policies

The debate regarding the importance of urban form in determining transportation patterns can be related to distinct theoretical and disciplinary perspectives on urban systems. The transport sustainability analysis presented in Section 3.3 focuses on how accessibility and urban form influence travel patterns, with the implicit assumption that land use planning is able to guide travel behaviour towards more environmentally efficient models. In Chapters 1 and 2 urban geographical and economic theory was discussed in which cities are conceptualised as dynamic socio-economic systems, evolving though shifting economic and technological eras, and through the interactions of firms and residents in urban markets. The latter dynamic market-orientated perspective provides an important counterpoint to sustainable planning theories, and raises the issue of how sustainability goals can be made compatible with the behaviour of urban residents and firms.

From the long-term urban evolutionary perspective the built-environment is a reflection of economic, social and technological change. Urban physical structures continually evolve to meet the accessibility demands of shifting modes of production and economic agglomerations, and their structure is related to the dominant transportation modes in their eras of major growth. Such relationships are clearly visible in the international urban comparison (Section 3.3.3), with strong relationships between infrastructure, urban form and travel patterns. Essentially a spectrum of solutions to the challenge of providing urban

accessibility has emerged in the evolution of cities. While on energy efficiency grounds low density US cities score poorly, environmental concerns were not part of historic market processes, and indeed largely remain market externalities in the present day. Car-dependent cities perform well by some metrics. One travel efficiency measure included in the *NK1990* dataset was journey to work time, shown in Figure 3.27, where North American cities typically have quicker travel times compared to their European counterparts[1]. Gordon *et al*. (1989) attribute such quick commuting times to the market-based collocation of firms and households, and have forcefully opposed centralised, high density planning proposals.
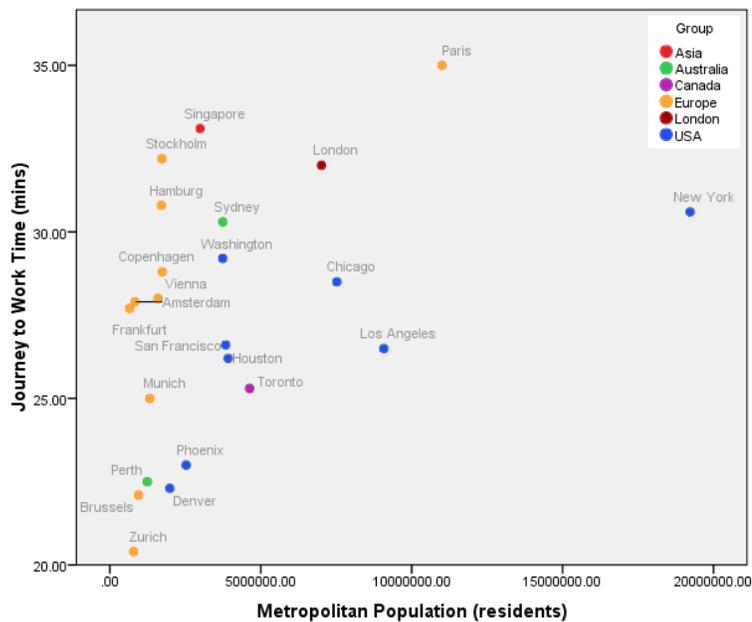
Figure 3.27: Graph Comparing Average Journey-to-Work Time with Metropolitan Population. Data source: Newman and Kenworthy (1999).

The individual choice basis of market perspectives emphasises the critical issue of social and political feasibility in sustainable planning debates. Populations choose housing locations based on the lifestyles they wish to lead (Kitamura *et*

---

[1] Note that city size also plays an important role in increasing travel times as shown in Figure 3.27. Furthermore the average journey-to-work travel time data does not consider travel times for non-car owners and related equality issues.

126

al., 1997) and to an extent choose their city of residence based on social preferences (Breheny, 1997; Glaeser *et al.*, 2001). In market-based societies, building environmentally benign housing that fails to attract residents will not meet sustainable development aims. Sustainable planning solutions must be regarded as attractive by the public and deliver a high quality of life for residents. This is both a 'delivery quality' and an urban culture issue. It is made more challenging in light of the suburban and exurban car-based lifestyles and aspirations that have dominated the second half of the 20th century (Breheny, 1995). Market-orientated perspectives apply equally to the demands and location choices of firms. The ability of transit orientated cities to facilitate the needs of contemporary knowledge-economy sectors is a key challenge in integrating urban sustainability needs with current economic trends.

It is clear that social and economic feasibility issues are of vital importance for the urban sustainability agenda. There needs to be a close integration of sustainability goals and market processes. There are many examples where these processes work in tandem, such as in the most sustainable European cities identified in the Newman and Kenworthy data, which achieve high levels of economic success and quality of life, alongside high environmentally efficiency. It is common however for markets to overlook environmental costs. For instance the decentralisation trends in recent decades have occurred during periods of low fuel prices that largely do not consider environmental impacts, and furthermore look increasingly uncertain in light of recent oil price fluctuations. In many cases significant intervention is necessary to guide markets to more sustainable outcomes, and this is where challenges of social and economic feasibility arise. A good example of UK policy seeking to unite sustainability and economic aims can be seen in the drive to reinvigorate city centres, through combining compact city and regeneration goals (Urban Task Force, 1999). Dysfunctional and unattractive centres contributed to decentralisation trends. The linking of post-industrial regeneration and sustainable development policies can be clearly seen in the focus on brownfield redevelopment, and investment in improving city centres. The relative success of this approach is a useful model for simultaneously achieving environmental and socio-economic policy goals.

3.4.2   Land Use and Transportation Policy Context

Based on the sustainable development agenda and the evidence base of built-environment and transportation relationships, policy responses have evolved to reduce vehicle miles by private transport and promote public transport and non-motorised travel. The planning policy tools to achieve this involve land use, transport and urban design measures. Land use measures include controlling new development, densities and mix of uses. Transport measures include public transport services, road space allocation between modes, traffic calming, parking policy and new infrastructure. Urban design measures include street layouts, public space provision and architectural design. Sustainable urban planning depends on integrating these various elements synergistically together. This research focuses on city-wide interactions between land use, transportation networks and accessibility. Local scale aspects of transportation planning and urban design are considered here only tangentially, yet this is not to imply these factors are insignificant, as they have very significant roles to play (Cervero, 1998; Urban Task Force, 1999).

The 'elephant in the room' for sustainable transport policy is typically fuel taxation which, as the previous international review of transportation energy use highlighted, is likely to be the most influential policy lever in influencing long term private vehicle use. Fuel taxation is however beyond the control of city governments and transport planners. At national level where taxation policy is determined, increases in fuel duty of the scale required to produce significant behaviour change typically have strong political opposition. Furthermore there are issues with the 'blunt instrument' of fuel taxation which cannot differentiate costs spatially or temporally. Pricing tools have been developed to better target private vehicle costs in areas of extreme congestion, with London's congestion charging scheme being a notable example, though these remain atypical cases at present.

A milestone land use planning policy document in the UK was Planning Policy Guidance Note 13 (DoE 1994) which established the core goals of concentrating higher density development at public transport nodes, allocating development to larger urban centres, avoiding major developments in locations

isolated from public transport, avoiding small new settlements, and promoting a mix of commercial and residential uses where feasible. This approach was expanded on to connect density levels and public transport services to a hierarchy of urban centres, as proposed in the Urban Task Force (1999) report (Figure 3.28).

Figure 3.28: Plans for a Transit Orientated City. Source: Urban Task Force (1999).

In cities with a strong history of public transport use, such as major European cities, the hierarchy of town centres envisaged in Figure 3.23 are, to a greater or lesser extent, already in place, having emerged in the 19th and early 20th centuries around railway and tram networks. For these cities planning priorities generally involve the improvement and better integration of existing services and the directing of new development to existing or integrated newly-built centres. Greater challenges exist where transit orientated structures have to be 'retro-fitted' on to automobile dominated cities. A conceptual diagram for such a process by Newman and Kenworthy (1999) is shown in Figure 3.29. When one considers the costs in terms of new infrastructure development and potentially land purchasing for such a process, in addition to established infrastructure and lifestyles built around car travel, clearly the challenges for this model are vast.

Figure 3.29: Transit Infrastructure Plan for Automobile Cities.
Source: Newman and Kenworthy (1999).

Amongst planning researchers concerned with sustainable development there is
a strong consensus around the nodal development ideas described above, but
there are differing views within this general approach. There have been critiques
of urban models that are dominated by the city centre, and that overly
monocentric structures bring long distance one-way congested travel patterns
(Maguire *et al.*, 2004). The alternative is for a 'flatter' hierarchy of centres
through polycentric structures, achieved through processes of 'decentralised
concentration' leading to larger sub-centres with more advanced employment
roles. This is broadly similar to the network city model (Meijers, 2007)
described earlier in Sub-Section 2.2.4.

3.5 Chapter Conclusions

This chapter set out to address Research Aim 2, which was *"to define urban sustainability in relation to the transportation sector, and analyse evidence on the links between urban form and transportation environmental impacts"*. We defined sustainability narrowly in terms natural resource management, ecosystem preservation and mitigating anthropogenic climate change. Transportation is amongst the largest sectors of energy consumption and carbon emissions, and has increased in relative terms as carbon emissions have fallen in other sectors. These increases have been caused by a five-fold increase in travel distances since 1960, overwhelmingly through increased car use, as individuals have sought to maximise their spatial opportunities in housing, employment, social and other activities. We concluded that the empirical analysis of transportation sustainability needs to focus on the two key issues of mode-choice and travel distances, as these factors underpin energy use and carbon emissions.

Urban form has been promoted as a means to achieving greater urban sustainability in travel patterns. There is massive international variation in per-capita transportation energy use and this variation is correlated with measures of urban form such as densities. The empirical research evidence however reveals complex cross-correlations between socio-economic, urban form and accessibility variables at various scales. Whilst the most sustainable cities are overwhelmingly high density, it is questionable whether urban form measures have a direct causal role in determining travel patterns, with socio-economic factors such as income, fuel taxation and car ownership being amongst the most influential in statistical models. The research evidence supports the theoretical argument that accessibility is the key geographical factor influencing travel patterns. Urban form measures such as density and land use influence absolute and relative accessibilities by various modes, as do transportation infrastructure and policies related to fares, fuel taxation and parking. The most sustainable cities achieve synergies between land use, transport, taxation, built-environment and cultural factors, and urban research needs to embrace this comprehensive

scope rather than narrowly focussing on any one particular aspect of urban structure.

What then are the consequences of these conclusions for the empirical measurement of urban structure and transport sustainability undertaken in the following chapters? Firstly we need to measure a comprehensive range of socio-economic, built-environment and accessibility dimensions, as these all have relationships with travel patterns. Key socio-economic factors include income, household structure and car ownership, whilst key built-environment factors include density and land use. These factors need to be considered in combination with accessibility measures, as accessibility drives property markets (as discussed in Chapter 2) and is closely connected to land use and socio-economic housing market outcomes. In terms of how accessibility should be measured empirically, several conclusions stand out from the review. These are the importance of regional accessibility (identified as the most influential factor in the meta-analysis in Section 3.3.4); the need to measure both trip origin and trip destination accessibility with arguments that trip destination measures may be more influential; and finally the desirability of more accurate accessibility measures based on network analysis.

The review has also identified a number of areas where research evidence is thin and additional analysis is needed. Given that regional accessibility is identified as being highly influential in statistical modelling, it is problematic that there is a lack of studies taking a comprehensive regional approach. This means that important questions regarding the sustainability and efficiency of city-region structures, such as monocentric and decentralised forms, cannot be sufficiently assessed. This research thesis advocates a meso-scale intra-metropolitan analysis as the most appropriate means of incorporating the influence of regional accessibility (and other regional housing and labour markets) into sustainable travel research, thus providing relevant evidence for strategic planning policy. Further to the point of research knowledge gaps, there is also a distinct lack of analysis exploring how employment dynamics and agglomeration (identified as central to changing urban structure in Chapters 1 and 2) are related to travel patterns. This relates to the above regional and trip

destination points, as well as the wider need to incorporate findings from economic geography into sustainable travel analysis. Analysing the relationships between employment geography and travel patterns is central to the research in the following chapters.

Chapter 4

Methodology for the Spatial Analysis of Intra-Urban Structure and Transport Sustainability

In this chapter we detail the methodology used to analyse relationships between urban employment geography and travel sustainability in city-regions. This chapter addresses Research Aims 3 which is "*to develop a methodology to analyse the urban form, employment geography, accessibility and transport sustainability of city-regions at an intra-metropolitan scale*". Section 4.1 provides an overview of the links between the urban processes of interest and the various empirical measures that can be used to measure them. This is followed by a discussion of the core methods of spatial analysis in Section 4.2, with a combination of mapping and statistical methods argued to be the most suitable approach for this research. Next the relevant spatial datasets are considered, beginning with socio-economic data in Section 4.3 and then considering built-environment data in Section 4.4. These are summarised in Section 4.5 in relation to their strengths and weaknesses in fulfilling the indicators specified earlier in Section 4.1. Finally spatial analysis techniques for analysing intra-urban structure using these datasets are then considered, with analyses of density and diversity in Section 4.6 and accessibility and travel patterns in Section 4.7, including the methodology for calculating intra-urban travel CO_2 emissions.

There is also a secondary research aim addressed in this chapter, which is Research Aim 4: "*to develop an empirical analysis identifying monocentric and polycentric forms, and relate this analysis to the urban structure indicators*". A

spatial analysis technique to differentiate between monocentric and various decentralised forms (including polycentric forms) is developed using the linked spatial measures of centralisation and concentration. This is presented in Section 4.6 as the technique is closely related to the other density and function measurements of urban structure.

4.1 Urban Structure Empirical Analysis Overview

4.1.1 Urban Dimensions and Linked Indicators

There are a great many possible empirical measures of urban structure, and we need to specify which are the key measures required to answer the main research question of the empirical relationships between employment geography and travel sustainability at an intra-metropolitan scale. These measures follow on from the conclusions of the previous three review chapters. We have advocated a comprehensive approach of including socio-economic, built-environment, accessibility and travel pattern measures. These urban dimensions are closely interlinked through the land use transport interactions and the urban market processes specified in Chapter 2. There are therefore typically multiple empirical perspectives on the same urban phenomena. Analysis can be simplified by grouping measures into linked processes and concepts as shown in Table 4.1. Table 4.1 details the key indicators selected for the analysis of employment geography, urban form and travel sustainability. These indicators are revisited in Section 4.5 after the urban data review sections to summarise how closely the data available fulfils these requirements.

First of all to analyse employment geography we clearly need measures of employment, with the location and volume of jobs. The dynamics of employment are particularly important, as this measure can be used to identify the degree to which processes of centralisation and decentralisation are occurring. Furthermore the polycentric urban forms and agglomeration discussion in Chapters 1 and 2 highlighted the importance of understanding particular employment types and their geography. We wish to identify agglomerations of productive knowledge economy industries that are driving

changes in urban form. The geography of economic activities can be explored through the concept of employment specialisation. This is a multi-faceted phenomenon connected to a range of empirical measures including industrial classifications, occupational classes, wages and rents (Table 4.1). The incorporation of wages and rents data relates to the agglomeration and urban markets discussion from Chapter 2, with specialist jobs and firms affecting labour and property markets. The intra-metropolitan study of employment specialisation is a novel research direction in this thesis, and at this stage we do not wish to be overly prescriptive regarding the most suitable empirical indicators. Various measures will be explored and tested in the analysis. Data sources to analyse employment geography are discussed in Section 4.3.

Table 4.1: Key Indicators for the Analysis of Employment Geography and Travel Sustainability

	Indicator Concept	Empirical Measures
Socio-Economic Geography	*Employment*	Workplace jobs Employment growth and decline
	Employment Specialisation	Business classification Occupational Class Rent Wages
	Household Type	Income Car Ownership Family structure Occupational Class
Urban Form	*Density*	Floorspace Floorspace growth / urban development Residential population & Workplace jobs
	Diversity	Real estate function Business mix
Travel Pattern	*Accessibility*	Regional accessibility by public transport Regional accessibility by car
	Travel Sustainability	Journey-to-work mode choice Journey-to-work distance Journey-to-work carbon emissions

Whilst employment geography measures are generally overlooked in sustainable travel research, related urban form measures of density and diversity are common (see Chapter 3). These measures can either be based on socio-economic geographies, or on built-environment geographies using real-estate data. The latter real-estate approach is used less frequently in sustainable travel

research, but is significant as built-environment measures provide a supply-side perspective on where space for economic activities is located, and how property markets and planning policy are interacting. Real-estate data sources are discussed in Section 4.4, and the spatial analysis techniques to measure density and diversity are detailed in Section 4.6. Although the focus of this research is on the influence of employment geography on travel patterns, it is also necessary to include residential geography measures as these have strong connections to travel behaviour. The key influences identified earlier in Chapter 3 include car ownership, income and family structure, as shown in Table 4.1. A number of measures can be considered from both residential and employment geography perspectives, such as occupational class and wages/income. Data sources for demographic variables are discussed in Section 4.3.

The last group of indicators in Table 4.1 are the critical travel pattern indicators. There are two related but distinct indicator concepts: accessibility and travel sustainability. Accessibility is concerned with potential travel interactions, whilst the travel sustainability measures analyse actual travel interaction data. The importance of accessibility has already been highlighted in the earlier review chapters. In terms of the empirical measurement of accessibility we advocating in Chapter 3 the need for a regional perspective, disaggregation by mode, and accurate network analysis measures. Spatial analysis techniques and issues regarding accessibility are discussed in Section 4.7. An important issue is the measure of travel cost used, with travel time modelled here rather than a more comprehensive generalised cost approach. Note that the opportunities in accessibility measures (the things urban actors are trying to access) are derived from the above socio-economic and urban form measures in Table 4.1. In Chapter 3 we discussed that local accessibility measures can be calculated in addition to regional measures. Local measures have not been included in this research due to their close correlations with the density and diversity measures and the likely duplication of indicators.

The final indicator concept is travel sustainability. This is based on the mode-choice and travel distance factors identified previously in Chapter 3. The trip pattern data used to calculate mode-choice and travel distances is discussed in

Sub-Section 4.3.3. The major issue with this data is what trip types are covered, and this research is restricted to journey-to-work. The problems with this restriction have been discussed earlier in Sub-Section 3.2.4. The mode-choice and travel distance measures can be combined into composite indicators, with carbon emissions being the focus here, as discussed in Section 4.7.

4.1.2   Indicator Data Requirements

Now that the empirical measures for the research have been specified, we need to consider what are the basic characteristics and qualities of the data sources needed for their inclusion in the research study. These requirements relate to the core data qualities of scale, temporal resolution, availability, and coverage in terms of the UK and other international contexts.

Whilst this research focuses on London and the South East, the aim is to develop a methodology that is widely applicable in many urban contexts. The issues of urban structural change and transport sustainability are universal across all cities, and there are many advantages to having methods that are transferable and allow the kind of comparative studies discussed in the Chapter 3 international city review. To facilitate transferability, national UK datasets are used as the basis of analysis rather than data specific to London. As a result of this approach, the methodology is directly applicable to other UK cities, and also can (with a degree of translation) be applied in other international contexts where similar business survey, census and property valuation data is available.

To allow the intra-metropolitan scale of analysis sought, we need data of sufficient resolution and extent. Issues of scale are discussed in more detail in Section 4.2, and in relation to specific datasets in Sections 4.3 and 4.4. The study area (defined in the next Chapter, Section 5.1) extends beyond the London government boundary, and therefore datasets need to cover the wider South East region. Another important issue is that of temporal resolution. Urban dynamics are critical to understanding how cities are changing and evolving, and to study urban dynamics we require datasets with multiple survey years. This issue is highlighted throughout the Section 4.3 and 4.4 datasets discussion.

4.2   Spatial Data Representation, Analysis and Geographical Information Systems

Before looking at specific urban datasets and methods of analysis, we firstly consider fundamental issues of spatial data representation. These relate to choices of data models and scale, which in turn influence the types of spatial analysis that can be performed. Recent improvements in spatial data sources have increased data resolutions and brought greater flexibility in representation. These developments are an essential advance in allowing the intra-metropolitan scale of analysis undertaken in this research. The development of GIS technology has moved spatial data representation beyond paper based maps to the rapid processing and analysis of spatial data, discussed in Section 4.1.5. Map based analysis can be complemented with statistical methods (Section 4.1.6).

4.2.1   Spatial Data Models

The development of information and knowledge relies on processes of reduction and abstraction to manage complexity. Scientific knowledge is developed and tested through models, which are abstractions of reality that mediate between theory and the real world (Morgan and Morrison, 1999). Modelling was discussed earlier in relation to systems theory, and further connected meanings of modelling include the definition of entities (ontologies) and the structure of data representation (data models). In the context of geographical disciplines, spatial representation and data modelling are central to the field.

Urban spatial data models can be usefully divided into iconic and symbolic models (Batty, 2001a). Iconic models represent geometric features that correspond to real world physical objects, such as are found in topographic mapping. Symbolic models on the other hand represent abstract spatial features, such as social and economic attributes, as is common in thematic mapping. The majority of urban geographical analysis is based on symbolic representations, including land use transportation models which use zonal-based flows and interactions. The forms of spatial representation are connected to issues of scale,

levels of detail and computational overheads. There are trade-offs in terms of the functionality and simplicity of different representations.

Following the digital revolution and development of Geographical Information Systems, two core digital spatial data models have been developed based on cartographic traditions: the vector and raster models. The vector spatial data model uses point, line and polygon structures- in mathematical terms geometric primitives (Raper, 2000)- to represent spatially discrete entities with linked aspatial attribute information commonly known as *features*. The connected attributes are stored within a relational database, the creation of which is itself a representational and data modelling process of entity creation and relation definition. The second fundamental data model structure is the raster model, which employs a regular grid tessellation of values (Raper, 2000). Vector models are used for iconic built-environment representations, where buildings are modelled as discrete objects, and for socio-economic zonal data, where zones are the discrete objects. Raster data models are used for continuous data such as elevation and remotely sensed imagery. The choice of data model has a number of important implications relating to the range of analytical processes which can be undertaken (Goodchild, 2005).

4.2.2   Scale in Geographical Analysis

Scale is a central concern of geographical research, both for theoretical and technical reasons. In theoretical terms scale dependence is an inherent feature of complex systems such as cities. Consequently studies must be carried out at the appropriate scale of analysis relating to the phenomena of interest (Openshaw, 1996), and ideally the interactions between processes at different scales should be understood. This typically requires analysis and testing at several scales to consider inter-scale relationships (Fotheringham and Rogerson, 1993). This research focuses on a meso-scale urban analysis to provide a city-region focus and complement the existing body of sustainability research at micro and macro scales (see Section 3.3).

The ability to perform analysis at any particular scale is dependent on the data available. Scale is more precisely defined through two related concepts: *extent*

and *level of detail* (Longley *et al.*, 2005). Scale describes the scope of the data representation, in terms of which features will be included and excluded, and the detail of those features that are included. The translation of real world entities into geometrical features inherently involves abstraction, guided by the chosen scale. For iconic spatial data, the complex geometry of real world objects must be simplified through processes of *generalisation*. Symbolic data representations are similarly affected by data manageability issues, with the additional factor of privacy considerations for socio-economic data. Consequently aggregate zonal data is the most common output format for socio-economic spatial data (Section 4.3).

There is a long established association between extent and level of detail in spatial data which expresses a fundamental trade-off in geographical research (Talen, 2003). Studies that cover a large spatial extent generally compromise their ability to include fine-scale features and processes. Conversely studies that focus on fine-scale processes face significant methodological and computational challenges in 'scaling up' such research to cover large geographical extents. This balance is significant both for spatial analysis, where large high-detail datasets increase methodological complexity and computation demands; and for visualisation, where there is a limited information density that can be legibly visualised on a page or screen (Skupin, 2000). The technical aspects of the scale trade-off in geographical research are increasingly being overcome, as innovations in fine-scale spatial data are opening up new possibilities for empirical urban spatial analysis. These new datasets are sufficiently *intensive* to analyse detailed form and function relationships and also sufficiently *extensive* to enable patterns to be generalised across entire city-regions (Batty, 2007a), and thus underlie the intra-metropolitan analysis of this research. These technical advances do not however solve the methodological complexity in combining intensive and extensive studies, and many analytical and visualisation challenges remain, as discussed in the following sub-sections.

4.2.3 Zonal Systems and Aggregation

Zones are the basic analysis units in much urban geographical research. The choice of zonal system or zonation has a series of consequences for the scale of processes that are represented by the data, and the computational demands on analysing that data. Highly disaggregate analysis is able to capture micro-level processes, but leads to increased computational demands and can be problematic for visual legibility and privacy. In city-wide studies, highly disaggregate visualisation and analysis can be cumbersome, with millions of units for analysis. Therefore aggregation methods are an important tool for generalising patterns and simplifying analysis.

A key reason why zonal systems must be scrutinised is the very common source of error known as the Modifiable Areal Unit Problem (MAUP) (Openshaw, 1984), which describes how changes in the spatial boundaries of a zonal system can alter the aggregate statistical properties of that system. The gerrymandering of political boundaries to influence election results is a classic illustration of this phenomenon. There is a second related aspect of the MAUP described as the scale effect, where the results of spatial statistical analysis change depending of the level of resolution, as a direct consequence of the scale dependence of geographical phenomena. In socio-economic contexts scale dependence is connected to the ecological fallacy, where it is statistically invalid to assume that aggregate properties of a zone apply to an individual within that zone. The MAUP affects all zonal data and is exacerbated by the fact that zonal boundaries are often arbitrary or fixed for reasons which are incidental to the purpose of study (Openshaw, 1996). Detailed spatial data is a means of minimising MAUP effects as discussed below.

Example zonations in urban geographical analysis as illustrated in Figure 4.1. Socio-economic zonations are very common in urban data, produced for administrative purposes. It is also possible to create zonal systems from built-environment features, such as street blocks. These are relevant to local urban planning tasks, and are more problematic to apply at higher level geographies. Finally abstract zonal systems without reference to any spatial features are possible, such as regular grids. Their independence from spatial features can be

advantageous for statistical analysis, as can the equal area properties of regular grids. Note that socio-economic zones generally sacrifice areal regularity in favour of the regularity of population variables between zones. Essentially the choice of zonation should follow from the desired scale of analysis and the spatial correspondence with the phenomenon of interest.

Micro-Scale　　　　**Meso-Scale**　　　　**Macro-Scale**

Built Environment

Buildings, plots, properties.

Street Blocks

Super Blocks

Street network

Major Streets

Fine Scale Grid

Meso-Scale Grid

Macro-Scale
(inter)national grid

Socio-Economic

Individuals, households,
Employees, firms.

Fine-scale Socio-economic
zones
(Output Areas, postcode
units)

Intermediate scale socio-
economic zones
(wards, councils)

Coarse-scale Socio-
economic zones
(counties, regions)

Travel Data

Individual travel diary-
survey

Zonal Interaction Matrices at varied socio-economic zone scales shown above

Figure 4.1: Aggregation Methods for Varied Scales and Zonations of Urban Spatial Analysis.

Processes of aggregation involve transforming spatial data between zonations. Transformations from detailed disaggregate spatial data to coarser resolution zone systems are the most straightforward and statistically reliable to perform.

Subsequently data at fine spatial scales is advantageous for scale flexibility. Another common task is to perform zonal transformations between data at similar resolutions. While spatial analysis techniques exist for such processes, MAUP errors will be introduced to a greater or lesser degree. Disaggregating from coarser resolutions to finer resolutions, is statistically highly unreliable and is the basis of the ecological fallacy. There are techniques from micro-modelling to address this problem by simulating populations using micro-survey data, but in standard spatial analysis, disaggregation transformations should be avoided.

4.2.4   Mapping and Visualisation

In the context of this research we employ thematic mapping techniques, that is visualisation methods that portray spatial variation, patterns and inter-relationships amongst spatial variables (Raper, 2000). Basic thematic maps display the spatial distribution of a single variable, and the visualisation challenge in urban research is often how multiple variables and relationships can be legibly visualised. One approach is to mathematically combine spatial variables into single composite variables (as discussed in the next section). An alternative visualisation techniques is three-dimensional mapping, where the extra dimension provides a means of combining multiple data layers and expanding the information content of the map. By extruding features in the third dimension, volume can be used as an intuitive means of displaying magnitude. Three-dimensional visualisation methods are used in Chapter 5 of this research to map urban density and function. Another important urban visualisation challenge is the mapping of flows, where each data item has an origin, destination, magnitude and potentially further properties. In Chapter 6 a series of techniques are employed in mapping journey-to-work data to summarise complex travel distributions.

Design decisions in thematic mapping affect the prominence of features, and influence how the map is 'read' by audiences (Monmonier, 1991). For scientific applications, the concern with mapping techniques is that design decisions can influence map interpretation and be used as a rhetorical device. A particularly important aspect of cartographic design for thematic mapping is numerical

classification. Variables with a large number of values are typically grouped into classes of similar value to simplify visual interpretation. Two algorithms used to determine the numerical intervals between classes are illustrated in Figures 4.2 and 4.3. In the example the Jenks Natural Breaks algorithm (Figure 4.2) emphasises differences in the middle range of the distribution, whilst the Equal Interval algorithm (Figure 4.3) focuses on the extreme values. The classification legend must therefore be made clear. It is beneficial to combine mapping with tables and statistical analysis to provide measures of spatial pattern independent of cartographic design.
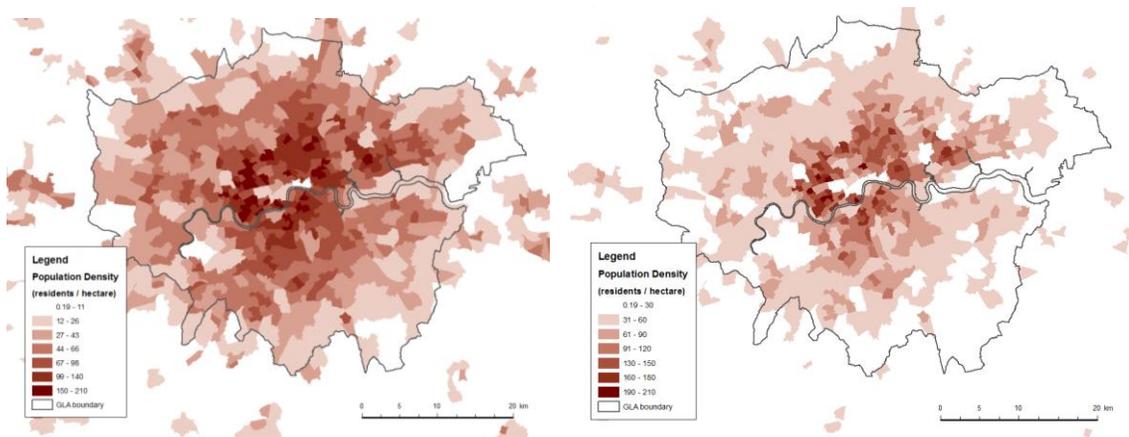
Figures 4.2 & 4.3: London Population 2001 using (left) Jenks Natural Breaks and (right) Equal Interval classification algorithms. Data source: Census 2001 (ONS, 2010a).

4.2.5   Geographical Information Systems and Spatial Analysis

Geographical Information System (GIS) technologies provide a range of functionality relevant to this research, including the ability to handle very large datasets, to integrate multiple data layers into composite indicators, and to combine varied forms of spatial analysis including topographic, topological and attribute based functions. GIS technology has revolutionised how geographical information is stored, analysed, and visualised (Longley *et al.*, 2005). Increasingly flexible and interactive means of using geographical information have evolved. We focus the discussion here on the use of GIS for urban research and planning. The core of GIS software is an integration of spatial database functionality; visualisation and cartographic design functionality; and spatial analysis functionality. The synergies between these tasks underlie the success of GIS as a software platform.

The core analysis functionality within GIS is based on manipulating and combining spatial data layers, with spatial location as the key means of integration. These processes of cartographic modelling involve overlaying layers, and performing arithmetic and logical functions either on individual layers or in combination (Tomlin, 1990). Spatial analysis can also be based on geometric properties, in terms of lengths, areas and distances between discrete features, and topological relationships between features. Finally aspatial database operations are a useful complement to spatial analysis, for the querying of the properties and classifications of the spatial features. Thus GIS functionality involves combining locational, geometrical, topological and attribute based analysis. This range of spatial analysis functionality is useful for integrated urban analysis, with built-environment data relating to geometrical analysis, socio-economic data to the attributes of spatial zones, and accessibility analysis to topological relationships.

While a range of GIS spatial analysis functionality is available in mainstream software, this does not typically include the more advanced spatial statistics and spatial modelling tasks that are common in fields such as environmental and land use transport modelling. Some researchers have criticised the view that GIS technology is equivalent to spatial analysis, arguing that the power of the graphical medium creates a pseudo-realism which is not necessarily matched by the explanatory power of the spatial models (Longley and Batty, 1996). While GIS technology has much to offer spatial analysis activities in terms of data storage and visualisation tasks, researchers have sought to define the disciplines of geographical information science (GISc) (Raper, 2000) and geocomputation (Longley *et al.*, 1998) independently from GIS.

4.2.6   Statistics and Spatial Analysis

Statistical techniques can provide a more rigorous complement to the visualisation and GIS analysis methods described above. The two main contexts for statistical methods in spatial analysis are as a descriptive exploratory tool, where calculations are used to identify patterns and hotspots to guide analysis in a generally inductive manner, and for inferential confirmatory analysis, where

statistical methods are used to test the significance of research hypotheses. Descriptive statistics include many common measures of distribution, such as mean and modal statistics, and measures of variance and deviation. Inferential statistics make predictions about future probabilities based on statistical samples. This includes significance testing of distributions for clustering, and correlation analysis for testing for relationships between variables, amongst many other techniques. Measures of statistical association between variables such as regression are of fundamental importance in scientific research for hypothesis testing. It must be borne in mind that regression and correlation measures can prove statistical association relationships but cannot prove causality, as discussed previously in Section 3.3 in the context of built-environment and travel pattern research. For this research thesis, statistics are used in the analysis of urban structure, principally measures of urban centrality and of function as discussed in Section 4.6, and in regression analysis to test relationships between urban form and travel patterns, as presented in Chapter 6.

Spatial statistics incorporate spatial location considerations into descriptive and inferential statistical measures. The spatial association between variables is fundamental to geographical enquiry, as succinctly expressed in Tobler's first 'law' of geography- "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). While spatial association is at the core of geographical analysis, in statistical terms it can invalidate a basic assumption of inferential statistics: the independence of the sample data, as nearby samples are likely to be correlated. This is referred to as spatial autocorrelation. Various means of measuring spatial autocorrelation have been developed, as discussed further in Section 4.6.

4.2.7   Summary

Forms of spatial representation are connected to issues of scale, levels of detail and computational overheads. There is a long established association between extent and level of detail in geographical analysis, with studies either covering a large spatial extent at a low level of detail, or a large spatial extent at a coarse level of detail. In light of scale dependence and MAUP issues, it is necessary to perform spatial analysis at the appropriate scale(s) for the process in question.

This research focuses on a meso-scale urban analysis to provide a city-region focus and complement the existing body of sustainability research at micro and macro scales.

There are a broad range of techniques for the study of spatial relationships, including mapping, GIS based analysis, and spatial statistics. Mapping is a ubiquitous method of information exploration, communication and analysis and is best employed in combination with statistical methods. The development of GIS technology has brought a profound revolution in how geographical information is stored, managed, edited, analysed and presented. Increasingly powerful tools to manipulate large spatial datasets have evolved, along with flexible and interactive means of using geographical information.

4.3 Urban Geographical Data: Measuring the Socio-Economic City

The most common applications for urban spatial analysis are based on socio-economic data, including the study of residential population characteristics, economic activities, and interactions such as travel patterns and migration flows. Here we focus on those datasets pertinent to intra-urban structure, economic geography and sustainable travel from a UK perspective. This includes firstly household and neighbourhood socio-economic data that relate to travel behaviour and mode-choice. Secondly we discuss workplace and business related datasets, which are relevant to firm location, employment specialisation and agglomeration processes. Finally interaction datasets that link residential and activity locations with travel interaction flows are reviewed.

In the Section 4.1 methodology overview, the aims of including urban dynamics and scale flexibility were discussed. These issues will be revisited in this section in regard to the spatial and temporal resolution of data, and sample size. There have been widespread improvements in socio-economic spatial data infrastructure in recent decades, including increased spatial resolution, richer attribute data, and online access.

4.3.1 Demographic Spatial Data- the UK Census and Postal Geography

In this section we discuss recent improvements to spatial demographic data, and how this data can be applied to the study of urban spatial structure and travel patterns. The GIS based mapping and spatial analysis of demographic data is now widespread in research, both in academia and in government. These advances have been underpinned by improvements in the spatial resolution and availability of census data in recent decades, providing access to a wide range of household based variables, including demographic, deprivation, employment, occupation type, car ownership and journey-to-work variables. These variables are significant in studies of travel behaviour as discussed in Section 4.1. One of the most significant absences from the UK census is income data. Subsequently the Office for National Statistics model average household incomes from other related data sources (Office for National Statistics, 2004).

The 2001 UK census included the addition of a significantly more detailed zonal geography known as output areas. In Greater London this increased the finest resolution of census data from 633 wards to 24,140 output areas. Consequently a significantly more fine-grained analysis of socio-spatial trends is possible. The output area geography was developed algorithmically to create zones of similar population size, social homogeneity, regular shape, and of a minimum size to preserve confidentiality (Martin, 2002). The decadal basis of the UK census has not however changed and therefore the temporal resolution is low. This can be problematic for the study of many urban processes operating at more frequent temporal scales, including travel patterns and residential location. Household survey based data can be used as a source of temporally richer demographic data, providing micro-level information and potentially filling in data gaps in the census.

Data resolution improvements are not restricted to census data, and can be seen in many areas of government and administrative data. Improvements to postal geo-referencing have been a significant development. The most detailed level of UK postal geography, unit postcodes, can identify locations down to the scale of approximately 14-17 properties (Thurstain-Goodwin and Unwin, 2000). This is

even higher resolution than output area geography, with over 50,000 unit postcodes in the Greater London area. All unit postcodes have been spatially referenced by the Royal Mail and subsequently released through products such as the National Postal Address File (Orford and Ratcliffe, 2007). The result of these improvements to postal spatial referencing infrastructure is that all address based data can be geo-referenced at postcode unit level in a straightforward manner and integrated into geographical analysis. This includes a wide range of administrative, property, business and other survey based data. Notwithstanding the high spatial resolution of unit postcodes, there are some problems. Postcode units are linear in nature, typically representing one side of a street, and so do not have an inherent area for zonal analysis. Zones can be manufactured with operations such as Thiessen/Voronoi polygons (de Smith *et al.*, 2007), although this does create a geometrically irregular geography. Note that these issues are further discussed in Section 4.4.4 relating to property and address based data.

4.3.2   Economic and Business Survey Spatial Data

As discussed in Section 4.1, we are principally concerned with aggregate employment and employment specialisation. The latter issues of specialisation relates to industrial disaggregation, wages and agglomeration processes. Property market data is also connected to firm location processes, and is discussed later under the built-environment section (Sub-Section 4.4.2). The intra-metropolitan study of economic data is atypical as the majority of aggregate economic analysis is at aggregate city and national spatial scales, concerned with macro-economic trends in employment and productivity. Subsequently many economic datasets (such as input-output tables) lack spatial detail.

The main source of spatially disaggregate economic data comes from business surveys. Business surveys need to be updated regularly to keep track of dynamics in businesses and employment. In the UK context, the major business survey data is the Annual Business Inquiry (ABI), which annually surveys a 10% sample of firms. The limited sample size introduces some analysis problems as described in Section 5.2. There are also further issues regarding changes in the format of the ABI overtime which affect time-series analysis,

again which are discussed in Section 5.2. Firm surveys typically classify business functions using Standard Industrial Classification (SIC) codes. The classification data can be used to analyse the spatial clustering of particular employment sectors and the relative specialisation of sectors, which are both relevant to agglomeration processes as shown in Chapter 5. Other datasets are used in the study of economic geography include taxation registration data for firm start-ups, and some micro-level studies have included the profitability of companies (Graham, 2003), though access to this kind of account data is typically restricted. Furthermore spatially disaggregate data on income by workplace is not available in the UK. For a more comprehensive sample of basic employment data, the UK census can be used. The travel to work data (discussed below) can be manipulated to produce aggregate employment data. The census also records occupational class data groups from Higher Managerial to Elementary activities which can be used to develop employment specialisation indictors, as pursued for the London Region in Section 5.2. Again the problem with the census data is the low temporal frequency.

4.3.3   Travel Interaction Data

As this research is concerned with transportation sustainability, it is essential to have empirical data measuring travel patterns. As with all socio-economic data, surveys can be classified into aggregate-level data sources and micro-level data sources. Aggregate surveys generally have high sample sizes, with the census being the most comprehensive journey-to-work sample. The trade-off with such a large sample size is in low temporal resolution and more basic attribute data provided. Micro-level data can provide more in-depth information such as comprehensive travel diaries, though inevitably sample sizes for micro-level data are much lower. This research seeks to understand detailed spatial trends across an entire metropolitan region. This approach favours data with comprehensive sample sizes, and so aggregate data is the focus of the analysis.

The most significant dimensions of travel for sustainability research are journey purpose, mode-choice, distance, time and cost. Furthermore for spatial analysis, the origin and destination locations are required. In the UK context census journey-to-work data records a near complete dataset of commuting flows for

the year 2001[1]. The 1991 census travel data used a 10% sample which prevents the reliable application of the methods developed here for years earlier than 2001. In the 2001 data a separate flow matrix is provided for each mode, including car driver, car passenger, bus, train, underground, cycling and walking trips. Only a single mode is recorded, and multi-modal trips are represented by only the main mode. This data is available at a high spatial resolution, down to census output area level.

The census journey-to-work data represents a very comprehensive source on commuting journeys in the UK for 2001. Indeed this data source has been underused in the analysis of transportation sustainability. Whilst distance and time information is omitted from the UK census, the geography is sufficiently detailed to estimate journey distances and times using network analysis (though this an extensive process, as described in Section 4.7). Sustainability related measures, such as energy use and carbon emissions, can be estimated using distance and mode-choice patterns, as detailed in Sub-Section 4.7.3. Additionally the data can be used as a spatially detailed measure of employment, by totalling the travel matrices by destination zones, as well as providing some basic means of classifying employment groups to complement the business survey datasets described in the previous section. These techniques are fully explored in Chapters 5 and 6.

Commuting is a significant journey purpose as it contributes to peak hour congestion, and is related to other business journeys (see Section 3.2). A comprehensive understanding of transportation sustainability does however require the consideration of all trip purposes. No equivalent dataset to the 2001 census exists for other trip purposes in the UK. The UK National Travel Survey is a micro-level household survey designed to track changes in travel patterns at

---

[1] Census interaction data in the UK is disseminated to academic users through the Centre for Interaction Data Estimation and Research website (cider.census.ac.uk). The tools provided through this service have been an essential component of this research thesis.

national and regional scales. This includes detailed travel diaries of all trip purposes. The sample size is 8,000 households annually, and detailed spatial referencing information is omitted. The National Travel Survey can identify macro-dynamics in travel behaviour (it was used in the earlier UK vehicle miles analysis in Section 3.2), but is unsuitable for the high level of spatial disaggregation used in this research. Overall the lack of comprehensive travel data relating to non-commuting trip purposes is a significant data gap in the UK and limits the analysis of transportation sustainability to commuting travel in this research. Note however that the methodologies developed are applicable to any transportation matrix data and could be straightforwardly applied to other trip purposes were the data available.

4.3.4 Summary

There have been widespread improvements in socio-economic spatial data infrastructure in recent decades, including higher spatial resolutions, richer attribute data, improved spatial referencing structures and improved data access with online interfaces. Census data improvements have been driving this change, developing a new detailed geography of output areas in the UK. Census data provides the core dataset of urban socio-economic spatial analysis, providing demographic, housing, employment and journey-to-work data at a high spatial resolution. The low temporal resolution is however a problem for many studies, and the trade-off between sample size, frequency and attribute depth is commonplace in socio-economic data. Intra-urban economic data is based on business surveys and provides detailed industrial classification data at high temporal resolution, but low sample size. Transportation analysis also needs to include data on travel flows, and comprehensive journey-to-work data is available through the census, though data on other journey purposes is not available. Built-environment data provides a useful complement to socio-economic geography, as discussed in the next section.

4.4   Urban Geometrical Data: Measuring the Built-Environment

We now move from the socio-economic data discussion to considering the spatial representation of the physical built-environment. The integration of built-environment data enables spatial patterns of residents, businesses and interaction flows to be grounded in the urban environment of buildings, streets and transportation networks. This allows relationships between socio-economic processes and urban form to be explored. Built-environment datasets are rarely used in the regional analysis of cities, and there is significant potential for research progress in a number of areas. These include a new empirical perspective on urban structure and dynamics using real-estate data; and significant improvements to urban accessibility measures using detailed network analysis.

4.4.1   Iconic Built-Environment Data

Here we discuss two major sources of built-environment geometry- topographic mapping and remotely-sensed data- and their integration in digital city models. Digital topographic mapping has advanced from the scanning of paper-based topographic maps to the development of detailed spatial databases of geometrical features linked to relational tables of attribute information. Improvements in geometrical detail and accuracy have occurred in tandem with integrated spatial data products that combine topographic mapping layers with other layers of spatial data (including the address referencing and transport network data discussed in the following sub-sections). In the UK context the national mapping agency the Ordnance Survey (OS) has been at the forefront of these advances with the release of OS Mastermap in 1999. This was an ambitious development of a seamless polygon topographic representation of the UK at 1 metre resolution linked to a relational database of feature attributes. All features have a unique reference and are classified into themes and groups, allowing basic urban features such as buildings, pavements, roads and parks to be categorised and mapped, as illustrated in Figure 4.3.

Figure 4.3: Ordnance Survey Mastermap Topographic and Address Layer Example.
Data source: Ordnance Survey 2007a.

Overall the advantages of topographic mapping sources for built-environment analysis relate to its comprehensive coverage and standardised spatial data format for use in GIS, as well as integration with other data layers. Shortcomings include the lack of socio-economic function information, and the limitations of the two-dimensional representation. The latter issue is problematic for representing many urban features including multi-storey buildings, bridges and underground metros. A partial solution is the application of remotely sensed data, which can be used in the representation of terrain and building geometry. The relatively recent innovation of lidar (light detection and ranging) has greatly improved remotely sensed elevation and terrain models with detailed resolutions (i.e. 1 metre and less) possible. This increased level of detail allows rich geometrical representations of features such as buildings.

The integration of topographic mapping and remotely sensed data enables the development of three-dimensional digital city models, as illustrated in Figures 4.4 and 4.5. On the visualisation front, the geometry of urban form provides an architectural context displaying and exploring urban spatial data (Batty *et al.*, 2001). Digital city models can also be used analytically as well as visually, though this functionality is generally not fully exploited (Batty and Hudson-Smith, 2002). The main relevance of digital city models for this research is in the analysis of urban density and form, though there are several further

155

applications such as building energy use and flood modelling (van Oosterom *et al.*, 2008). The implementation of digital city models within a GIS environment allows a greater range of spatial analysis functionality, as the model can be combined and analysed with other kinds of urban spatial data, as shown in Figure 4.4. A further advance on this visual overlay method is to develop a spatial database of the built-environment, and store attributes associated with buildings and built-environment features, as shown in Figure 4.5. A spatial referencing model linking building geometry to socio-economic geography is required for this technique, as discussed in the next sub-section.

Figure 4.4 & 4.5: Virtual London 3D City Model with (left) Nitrogen Dioxide Emissions, and (right) Querying Building Attributes. Source: Batty (2007a).

4.4.2   Real-Estate Data

Real-estate data provides a distinct empirical perspective on urban form and function. It is of particular interest in the context of this research as it bridges between the physical built-environment and socio-economic urban dimensions. Typical real-estate measures include physical measures of the size of premises and socio-economic measures of their function. Potentially market valuation data can also be sourced from real-estate data to be used in property analysis. The application of real-estate data to the study of urban dynamics requires survey data across multiple years, as demonstrated later in Section 5.3.

Typically real-estate data is micro-scale in form, describing the properties of individual premises. This is advantageous for spatial analysis as it improves

scale flexibility (see Section 4.2). Spatial analysis of real-estate data depends on utilising a spatial referencing model for property, the most frequently used being postal address and cadastral (land-ownership) systems, with postal geography being the framework referencing system in the UK (Longley and Mesev, 2000). For meso-scale and macro-scale urban studies it is relatively straightforward to aggregate real-estate data to postal geographies. This is a sufficient level of detail for many studies, and indeed an aggregate grid approach based on unit postcode analysis is used in this research (see Section 5.3). Micro-scale spatial referencing allows the matching of addresses to individual building polygons and plots, with potential advantages for the study of fine scale urban processes. The data in the UK is not yet mature and accurate enough to be used at this scale[1].

The building-level spatial referencing of real-estate is not however essential for analysis, as UK postcode units are highly disaggregate, and property taxation and business surveys contain the results of micro-level surveys. The data used in this research is from the UK property tax listings, which provide accurate and comprehensive measures of the size and basic function of premises. As

---

[1] Micro-scale spatial address referencing in the UK began with the spatial positioning of individual postal delivery points by the UK postal authority. The Ordnance Survey released Address Layer (Longley and Mesev 2000) and subsequently Address Layer 2 which have integrated mail delivery point data with the Mastermap topographic layer. These recent advances are in the early stages of creating a comprehensive micro-scale built environment geography. These micro-scale developments are not however a final solution, due to the lack of three-dimensional data and problems in distinguishing between addresses, premises and households. Multi-storey buildings contain multiple vertical levels of changing ownership and function. This kind of micro-scale variation is not possible to model using two dimensional topographic and address based data. This limits the micro-scale accuracy for property based spatial analysis. For example floor-spaces cannot be derived accurately, as variation in the third dimension (number of floors, ceiling heights) is unknown. This problem is also related to the distinction between addresses and premises. Multiple businesses may occupy floors of a building (premises) but the building may have only a single postal address.

premises are internally surveyed, there are significant accuracy advantages estimating property sizes compared to topographic mapping approaches. These floorspace datasets can be used for detailed density measures of the built-environment.

In addition to floor-space measurements, real-estate data is also relevant for understanding urban function. Classifications of property use are essentially measures of function (with some caveats as discussed in Section 5.3), and have some similarities to employment classification data. The categories provided relate to basic urban functions such as office, retail and residential activities. These categories have similarities to the use classifications that are a mainstay of local urban planning, and this connection is beneficial for the application of real-estate data in urban planning research. The last category of real-estate data relates to property valuation. Rental and property price data are relevant for a number of research areas, including land use modelling, urban development and investigating agglomeration economies. This is highly relevant data for the economic market based approaches to understanding cities that were outlined in Chapter 2. This research focuses on commercial property, and there are few UK studies using commercial real-estate data. An example of such a study looked at property value uplift from new transport infrastructure (Atisreal and Geofutures, 2005).

In summary, real-estate data can provide useful empirical measures of urban form, function and property value that connects built-environment and socio-economic urban perspectives. The data is typically at premise level, thus providing highly disaggregate data which can be employed in analyses of urban density and functional diversity given a spatial address referencing model. Linking data at zonal scales, such as postcode units, is now a relatively straightforward process, whilst micro-scale models are still under development. Real-estate data is suited to the study of dynamics provided access to temporal data can be obtained.

4.4.3   Transport Network Data

Measures of distance and accessibility are used frequently in spatial analysis to assess spatial relationships and the potential for interaction. Network representations allow transportation infrastructure to be represented and more accurate network accessibility measures based on actual routes and services (rather than straight-line distances) can be calculated. The basic structure of a network consists of nodes and links. Links determine the connectivity between nodes, and have attributes describing the cost of traversing the link, such as distance or time. Public transport modes are the most directly amenable transport system for network representation, with stations/stops represented as nodes and public transport services represented as links between these nodes. Data on the spatial location of public transport interchange points and service timetables can be sourced from public transport agencies. There has been significant progress in standardising the data formats of these databases and increasing availability over the web with initiatives such as NAPTAN and TransXchange (Department for Transport, 2010). These datasets do not yet include public transport fares information, and monetary costs have been excluded from the accessibility analysis here.

The representation of road and street transport infrastructure in graph form is less straightforward than rail transport. Essentially road and street infrastructure is shared by multiple modes: private cars, taxis, buses, cycles and pedestrians. The competition for space and accessibility between these modes has many implications for the functioning of cities (as discussed in earlier chapters) as well as for the representation this system in network form. Firstly network connectivity is mode-specific, and consequently the same infrastructure may need to be abstracted differently depending on the transport mode of interest. For instance an A-road provides high accessibility to motorised transport, but may have low accessibility for cycles and can act as a barrier for pedestrian travel. Secondly the complexity of the network and flexibility in movement of private transport leads to representational ambiguities in how certain features are to be abstracted. Irregular junctions and public space features such as squares and parks, do not directly translate into node and link structures.

Road centre-line data is a common mapping product for the representation of road networks. Essentially this vector data represents roads as lines, and junctions as nodes. The rules defining how complex junctions are represented depend on the scale of the representation. Road lines are given attributes such as the number of carriageways and the road type classification. The primary applications for this data are for vehicle routing, thus the network representation is designed for private vehicle travel. Information on infrastructure for other modes (such as pavement provision, bus lanes and cycle lanes) is generally absent, as are links that do not serve private vehicles, such as pedestrianised streets and paths[1]. While road centre line networks have not been designed specifically to cater for non-motorised modes, they do describe the core of the street network and can be modified to provide a useful base network for pedestrian, bus and cycle travel. For example a pedestrian network can be created by excluding road types without pavement provision (such as motorways) and augmenting the network by adding pedestrian paths, provides a reasonable approximation of pedestrian accessibility. This approach does however overlook micro-scale issues such as severance, road crossings, bridges and underpasses. Cycle networks can also be represented in a similar vein. Data on cycle infrastructure is currently poorly catered for in the UK from commercial products, and crowd-sourced data products such as OpenStreetMap provide a useful alternative.

Road centre line data is by no means the only possible network representation of urban transport infrastructure. A contrasting body of work has emerged from the architectural research field of space syntax (Hillier, 1996). The aim of this research is to create a network based on cognitive perceptions of urban public space. The network is formed by lines of sight, with the intention of representing pedestrians' cognitive maps of street networks. Travel cost or

---

[1] To address this issue, the Ordnance Survey released an early version of an urban pedestrian paths layer for their Integrated Transport Network data product in 2010 which was unfortunately too late to be used in this research.

accessibility is defined by the route complexity (e.g. the number of turns represents travel cost) in contrast to distance-cost accessibility approaches. While there have been critiques regarding how robustly and unambiguously line of sight networks can be defined (Batty, 2004), space syntax does successfully emphasise the important role that spatial cognition plays in pedestrian accessibility.

4.4.4   Summary

The physical built-environment can be directly represented using iconic spatial models. Sources of iconic spatial data such as topographic mapping and remote sensing have been greatly improving in accuracy and sophistication in recent years. This has stimulated the development of digital city models. GIS can be used as a platform for developing built-environment models, integrating the iconic data sources with socio-economic data. This relies on accurate spatial referencing models, and spatial address referencing has also been improved and integrated with topographic modelling products. A particularly important resource for this research is real-estate data, which offers a distinct empirical perspective on urban form, function and development that can be used for detailed built-environment measures of urban density and land-use.

Network representations are a very common and powerful means of abstracting transportation infrastructure allowing topological and connectivity analysis to be performed. Road centre line data is the most common geographical network product. This is designed for motorised travel routing, and needs modification to consider non-motorised modes. Once a network has been created a range of analysis functions are possible, as described in Section 4.6.

4.5 Indicator Datasets Summary: Strengths and Weaknesses

We now return to the indicators set out in Section 4.1 and discuss how closely the data available matches the desired indicator measures. The mapping of indicators to datasets is shown in Table 4.2. Relevant data has been found for nearly all the required indicators, the exception being wages in the employment specialisation category. A number of measures use two datasets in combination to try and overcome temporal or spatial shortcomings from using a single dataset in isolation. For example the large sample size and low temporal resolution of the census can be usefully combined with the shorter term dynamics of survey data such as the Annual Business Index.

Table 4.2: Strengths and Weaknesses of Datasets Used for Indicators

	Indicator Concept	Empirical Measures	Datasets Used	Strengths	Weaknesses
Socio-Economic Geography	*Employment*	Workplace jobs Employment growth and decline	Census 1991,2001 ABI 1998-2008	Census comprehensive sample, whilst ABI shorter term dynamics. National datasets, wide coverage.	Lack of up-to-date data from census. ABI has 2006 discontinuities.
	Employment Specialisation	Business classification Occupational Class Rent Wages (not available)	ABI 1998-2008 Census 1991,2001 Aggregate VOA Survey 2005	Again combining census and ABI. Aggregate VOA data also a national dataset.	Again problem with up-to-date census data. Also earliest VOA data from 2005, so not same year. Wages data not available.
	Household Type	Income Car Ownership Family structure Occupational Class	ONS Estim. 2001 Census 2001 Census 2001 Census 2001	Comprehensive national datasets, large sample.	2001 only.
Urban Form	*Density*	Floorspace Floorspace growth / urban development Residential population & Workplace jobs	VOA Survey 2005 London Develop. DB 2001-2010 Census 2001	Detailed VOA Survey 2005 acquired, address level floorspace and functional data. Development database for dynamics.	Detailed VOA survey GLA only, so no wider region. Lacks dynamics, so augmented with London development database.
	Diversity	Real estate functional mix	VOA Survey 2005	Again detailed VOA Survey 2005.	GLA only, no dynamics.
Travel Pattern	*Accessibility*	Regional accessibility by public transport Regional accessibility by car	OS MM Networks Transxchange PT timetable ITIS Ecourier 2007 Road speeds	OS Mastermap and Transxchange national datasets. Augmented with accurate road speed data.	No PT fare information. Road speed data specialised datasets, not yet widely available.
	Travel Sustainability	Journey-to-work mode choice Journey-to-work distance Journey-to-work carbon emissions	Census 2001 Journey-to-Work data	Comprehensive national dataset, large sample.	2001 only, journey-to-work only. Distance and carbon emissions not included and need to be calculated.

There are a number of issues regarding temporal discrepancies between datasets. This is particularly the case when trying to combine the VOA real-estate data with census data, as the VOA data was only available for 2005 for this research. Another problem with the VOA data is that the detailed address level dataset was only available for the London government area rather than the wider region (although the aggregate ward level data is available nationally). These issues are further discussed in Section 5.3. The real-estate data is augmented with information from the London government development database to allow the study of real-estate dynamics in the Chapter 5 analysis.

The major travel pattern data source is the 2001 census journey-to-work data. This dataset does not include vital distance and time information, thus these need to be calculated using GIS methods, as described in Section 4.7. Relying only on the 2001 census data means that the most recent travel dynamics in the study region are not analysed. This issue could be overcome with the 2011 census data, but this will not be available until 2013. Furthermore trip purposes other than journey-to-work are not analysed.

Overall the aim of combining socio-economic, built-environment, accessibility and travel pattern urban analysis is certainly possible with available datasets, but does require drawing on a wide range of sources and using techniques to overcome various temporal and spatial discrepancies between these different sources. The main current restriction of the methodology is that the detailed travel sustainability analysis is confined to journey-to-work travel in 2001 only.

4.6 Techniques for the Analysis of Intra-Urban Structure

This section outlines core spatial measures of urban structure, including density, urban function and centrality. These concepts use the socio-economic, built-environment and travel datasets discussed in the previous sections and apply them to the analysis of urban spatial patterns. As this research is concerned with the properties of monocentric and polycentric forms, the overriding theme of this section is the analysis of urban centrality and the definition of urban centres. This leads to the discussion of techniques for the empirical identification of monocentric and polycentric forms in Section 4.6.3.

4.6.1   Density of Urban Activities and the Built-Environment

Density is a universally used concept in geographical research and urban planning, linking between socio-economic and built-environment contexts. High densities indicate investment in the built-environment and are connected to property markets and rent (explored in Chapter 5). Whilst the earlier discussion of sustainable travel relationships indicates that density does not have a direct causal role in travel patterns (Section 3.3), it is typically strongly correlated with accessibility and is a necessary if not sufficient condition of sustainable urban travel patterns. There are however a wide range of ways to measure density, and these are sensitive to the scale and zonation effects described earlier in this chapter.

Density is ostensibly a simple concept, measuring the ratio of a spatial attribute to an areal unit, as for example in the common application of mapping of population and employment distributions. The meanings of 'high' and 'low' density have acquired many normative associations, with extreme overcrowding in the industrial era leading to connections between high densities and urban-ills such as poor health, poverty and crime. The garden city movement, in publications such as Unwin's (1912) *Nothing Gained by Overcrowding*, responded by proposing new low density settlements. Early measures of residential density included dwellings-per-hectare and population-per-hectare, proposed as an alternative for mixed housing areas (Ministry of Health, 1944). Density indicators can be calculated over a range of areal units, using the

zonations described earlier in Section 4.1. The spatial units typically used in local planning tasks are based on built-environment features such as building footprints, plots and street blocks, while larger scale geographical analysis of population distributions typically uses socio-economic zones.

Density measures are dependent on their functional context. This can be seen in the contrast between the residential population density map in Figure 4.6 and the employment density map in Figure 4.7, with the residential population spread across the inner-city and the suburbs and employment strongly concentrated in the city centre. This indicates that using residential or employment measures in isolation will only capture one aspect of urban populations, and indeed the combination of residential and employment populations, or *activity density*, is argued to be a more representative measure of urban density (Cervero, 2002). This link between density measures and functional classification is discussed further in the next sub-section.
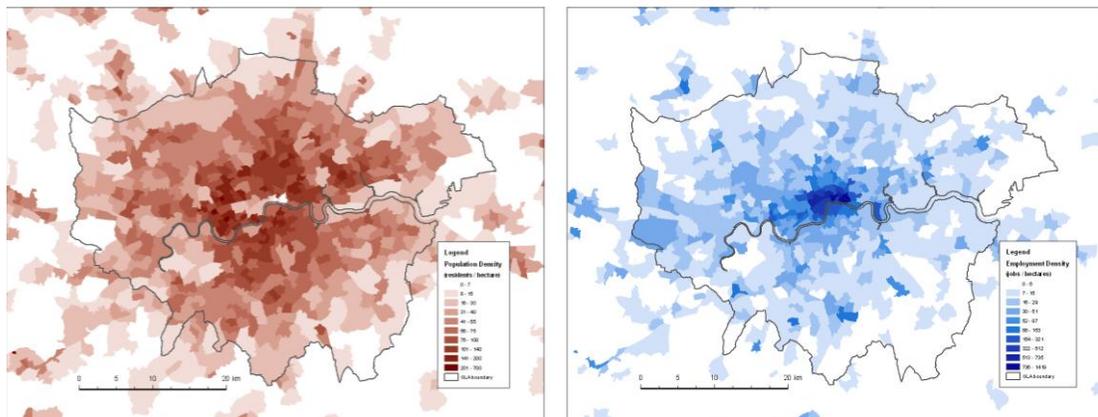
Figure 4.6 & 4.7: Greater London Residential Density (left) and Employment Density (right) at Ward Scale. Data Source: Census 2001 (ONS, 2010b).

As a complement to the socio-economic measures of density above, we can consider density measures of the built-environment. Built-environment measures can offer additional perspectives on processes such as urban development and property markets. The traditional dwellings-per-hectare indicator of built-environment density is of limited general use as it overlooks property size variation and non-residential functions. An alternative approach is to consider floor-space density as a physical measure of how 'built-up' an area

is. The ratio of floor-space to land area is known as a floor-space index or floor-area ratio (Pont and Haupt, 2007). This measure is typically applied to local planning analysis, though it is possible to measure floor-space density in city-wide analysis, as pursued in Section 5.3 of this thesis. Relationships between floor-space measures and population and employment density are potentially of interest as measures of occupancy and intensity of activity in the built-environment context.

Floor-space index measures are one of a range of potential measures characterising local urban form. This research follows a city-region meso-scale analysis and only touches on local architectural contexts, yet it is necessary to discuss urban design as it can be highly significant in travel patterns (Cervero, 1998; Sherlock, 1991). For any given aggregate density a variety of built form combinations are possible, as for example in the contrast between the Corbusier-style tower-and-park arrangement and a terraced low-rise layout shown in Figure 4.8. These design variations influence public space, the pedestrian environment, car parking availability and local accessibility by public transport and non-motorised modes. The variations in the urban forms in Figure 4.8 can be captured quantitatively using open space and ground space indices (Pont and Haupt, 2007). This research has not calculated local built-environment measures for city-regions, and it would be valuable for future research to explore this.

Figure 4.8: Urban Design Variation at a Fixed Density.
Source: Andrew Wright Associates, from Urban Task Force (1999).

In summary, density is a longstanding concern of geographical and urban planning analysis, and can be considered from socio-economic and built-

environment perspectives. Density measures are closely linked to the urban function being considered, with residential and employment populations being the most commonly analysed. Built-environment density measures are generally used for the analysis of built form planning at local urban scales, as they can highlight variations in urban texture pertinent to design and local environment concerns. It is also possible to apply built-environment density analysis at city-wide scales as is pursued in Chapter 5 of this thesis.

4.6.2   Classifying Socio-Economic Functions and Mix-of-Uses

Urban function measures classify socio-economic activities in cities. Function is a fundamental spatial property of urban structure, and is relevant to a range of research topics, such as land-use modelling and urban travel demand. In this section we first discuss the importance of function in terms of urban diversity and sustainable travel, and then discuss the empirical measurement of function in terms of classification systems and specialisation/diversity measures.

One of the main applications of urban function data is in the analysis of mix-of-uses. Functional diversity is a prominent feature of urban sustainability policies, where the provision of local services is argued to minimise travel distances and support local communities (Ewing and Cervero, 2001). The modernist tradition in urban planning promoted the spatial segregation of socio-economic functions through zoning, intended to improve urban efficiency and serve the dispersed mobility patterns of the automobile. Mono-functional development has been criticised as clashing with the traditional urban fabric. Jacobs (1961) influentially argued that a complex and fine-grained mix-of-uses at pedestrian scales underlies the effective functioning of urban centres as vibrant and safe places to live. Jacobs explicitly argues for a synergy between functional diversity and population density, arguing that higher population densities provide suitable demand for diverse functions, and stimulate specialisation and further diversification. While Jacob's ideas predate the current sustainability agenda, there is much common ground in terms of championing high densities, local community interaction and pedestrian environments. Subsequently the promotion of fine-grained mix-of-uses has become a central policy of sustainable urbanism.

Measures of urban function are also relevant for understanding economic specialisation and agglomeration. Strong localisation economies are generally reflected in high concentrations of employment in particular industries. These clusters can be identified using business survey data. There are further relationships between specialisation and polycentric forms, with different intra-urban centres specialising in particular economic roles depending of the comparative advantages of different locations (discussed in Sub-Section 1.2.2).

The classification system used has a significant bearing on how urban function and diversity are measured. Detailed employment based classifications use Standard Industrial Classification systems at various levels of detail (see Section 4.3.2). Local urban planning practice generally uses a property based classification of function. Core classes include residential, office, retail, public service and industrial activities, related to local planning concerns such as public access, safety and licensing. The choice of classification system is important as it can in certain contexts determine whether an urban area is measured as diverse or homogeneous. For instance using a basic residents-jobs balance measure a specialised business centre such as Canary Wharf in London would be largely mono-functional, as the centre's massive employment concentration dwarfs its residential population. Yet a study based on the classification of business services would find the same centre to be highly diverse, as Canary Wharf features a complex network of advanced producer service industries in finance, business services and publishing (discussed further in Chapter 5). Thus different empirical approaches are needed for analysing diversity in relation to live-work integration compared to economic diversity.

The ratio of residential population to employment is a basic indicator of mix-of-uses commonly referred to as the jobs-housing balance. This provides a general description of whether an area is primarily an employment centre or is residentially focussed, as shown in Figure 4.9. It has been argued that a balance between jobs and residents at intra-urban scales should be associated with more localised journey-to-work patterns (Cervero, 1989). Subsequent research has cast doubt on whether this basic measure can capture the complex residential-location and jobs-market processes that underlie commuting behaviour

(Cervero, 1996a; Giuliano and Small, 1993). This research points to local jobs-housing balance spatial distributions being an outcome of agglomeration and property market processes (Chapter 5) and that jobs-housing balance measures require a regional perspective (Chapter 6).
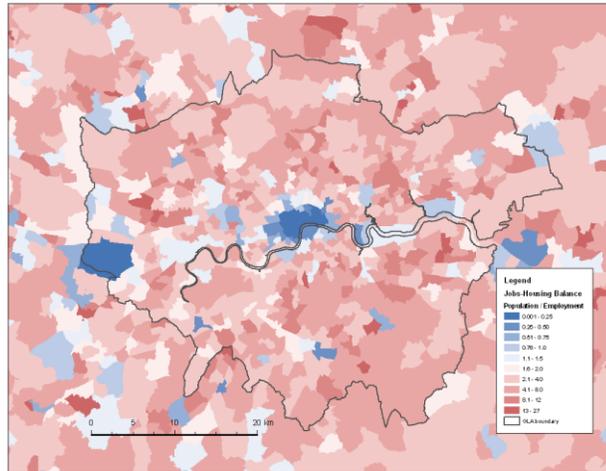
Figure 4.9: Greater London Jobs-Housing Balance. Data Source: Census 2001 (ONS, 2010b).

Employment specialisation is most commonly measured using the location quotient shown in Equation 1, which takes the ratio of the local concentration of a category (typically employment in an industry) to the regional/national average concentration. This has applications in the identification of employment agglomerations, as pursued in Chapter 5.

Equation 1: Location Quotient

$$LQ_i = \frac{e_i/e}{E_i/E}$$

Where:

e_i = Local employment in industry i

e = Total local employment

E_i = Reference area employment in industry i

E = Total reference area employment

The location quotient measure describes a single category while diversity statistics need to analyse multiple categories simultaneously. The index of diversity or variation, shown in Equation 2, is a common measure which sums the squares of the proportion of entities in each category. With this measure a completely homogenous population would have an index score of 0, while a perfectly heterogeneous population tends towards 1. The index of diversity is

based on relative proportions, and effectively measures the balance of different functions within a zone. As real world classification systems have finite numbers of categories, the measure is sensitive to the total number of categories used. Many other approaches to measuring diversity are possible. Dissimilarity indexes have been used to measure relationships in land use between nearby zones (Cervero, 2002). Batty *et al*. (2003) propose a joint density-diversity index that measures both functional diversity and absolute concentrations in terms of density, as shown in Equation 3.

Equation 2: Index of Diversity/Variability

$$D = 1 - \sum_{i=1}^{N} p_i^2$$

Where:

p = proportion of individuals or objects in a category

N = number of categories.

Equation 3: Density-Diversity

$$D = 1 - \sum_{i=1}^{N} p_i^2$$

Where:

p = proportion of individuals or objects in a category

N = number of categories.

In summary, urban function is a vital dimension for understanding urban spatial structure. Functional diversity has an important role in policies encouraging local travel patterns, whilst functional specialisation is linked to agglomeration economies. Measures of function vary from basic live-work classifications to more sophisticated employment and property measures which can be used to calculate specialisation and diversity indices. Functional measures are highly dependent on the classification system used.

4.6.3   Urban Centrality: Identifying Monocentric and Polycentric Forms

This sub-section addresses the research aim of developing a methodology for the empirical identification of polycentric forms. The spatial dimensions of urban structure discussed previously- density, mix-of-uses and indeed

accessibility- are interrelated aspects of urban centrality, and urban centrality is the basis for the empirical measurement of monocentric and polycentric forms. The quantitative spatial analysis of urban centrality is needed to locate and define intra-urban centres, and to analyse their properties. This analysis requires the consideration of scale dependence and urban hierarchies as discussed below.

The definition of urban centres is a long-running concern of geographical analysis. Murphy and Vance (1954) classically defined the Central Business District of cities in the USA based on the concentration of retail and office premises, high land values, and the intensity of pedestrian and vehicular activity. To this list we could add many other elements, such as transportation accessibility, concentrations of services, civic centres and landmark buildings. A particular challenge for defining the urban centres of contemporary cities is that newer centres at the urban fringe often contrast with the traditional centres, being relatively low density and with a narrower range of functions. One of the most straightforward and commonly used means of defining urban centres is to analyse employment clusters (Giuliano and Small, 1991; Wang, 2000). This approach is clearly of direct relevance to economic geography and commuting, and is applied in this thesis in Chapter 5. Giuliano and Small (1991) define employment centres as groups of adjacent zones where: 1) each individual zone exceeds an employment density threshold; and 2) the collective employment total for the zones exceed a total employment threshold. Clearly the limitation with such an approach is the arbitrary thresholds, which influence the number of centres identified. Threshold values can be defined according to a global cut-off value or a local sub-regional value, which is useful for contexts where sub-centres vary across the city-region (as is found in the London region study area). More sophisticated approaches to identifying employment centres include locally weighted regression models (Redfearn, 2007), and the use of clustering statistics, as described below.

A key consideration in the analysis of centres is the existence of urban centre hierarchies. Earlier in Section 2.1 we explored the hierarchies or networks of urban centres that exist from the perspective of central place and economic location theory. These hierarchies result from the interplay of transportation

costs, agglomeration economies, dispersion forces and economic specialisation. Urban hierarchies can be found for many functions including retail, public-service and office activities, and exist to varying degrees at intra-urban and regional scales in all cities. It is highly improbable for a city to be entirely monocentric with absolutely all economic activities in a single centre; whilst similarly no real-world city has a pure polycentric pattern with activities exactly distributed across multiple centres. Instead the terms monocentric and polycentric are used to describe the relative dominance of centres within a city; they are trends in a spectrum of spatial activity hierarchies.

The existence of urban centre hierarchies is directly related to the scale dependence of urban centrality measures. Essentially the pattern of urban centres display fractal properties (Batty and Longley, 1994), and the number of centres measured will be influenced by the scale of analysis. The extent of the analysis is also significant as potentially a city could be monocentric at the intra-urban scale while being part of a larger polycentric network at the regional scale. Urban decentralisation trends are increasingly blurring distinctions between these scales, as greater mobility draws neighbouring settlements into functionally unified urban regions (see Section 1.2).

Monocentric and polycentric spatial distributions can be defined empirically using two linked measures of spatial concentration: centralisation and clustering (Anas *et al.*, 1998). Centralisation describes the degree of concentration around a single centre at the metropolitan scale, whilst clustering analyses number and size of sub-centres. By combining these two measures of centralisation and clustering a matrix of idealised urban centre hierarchies can be postulated, as illustrated diagrammatically in Figure 4.10.
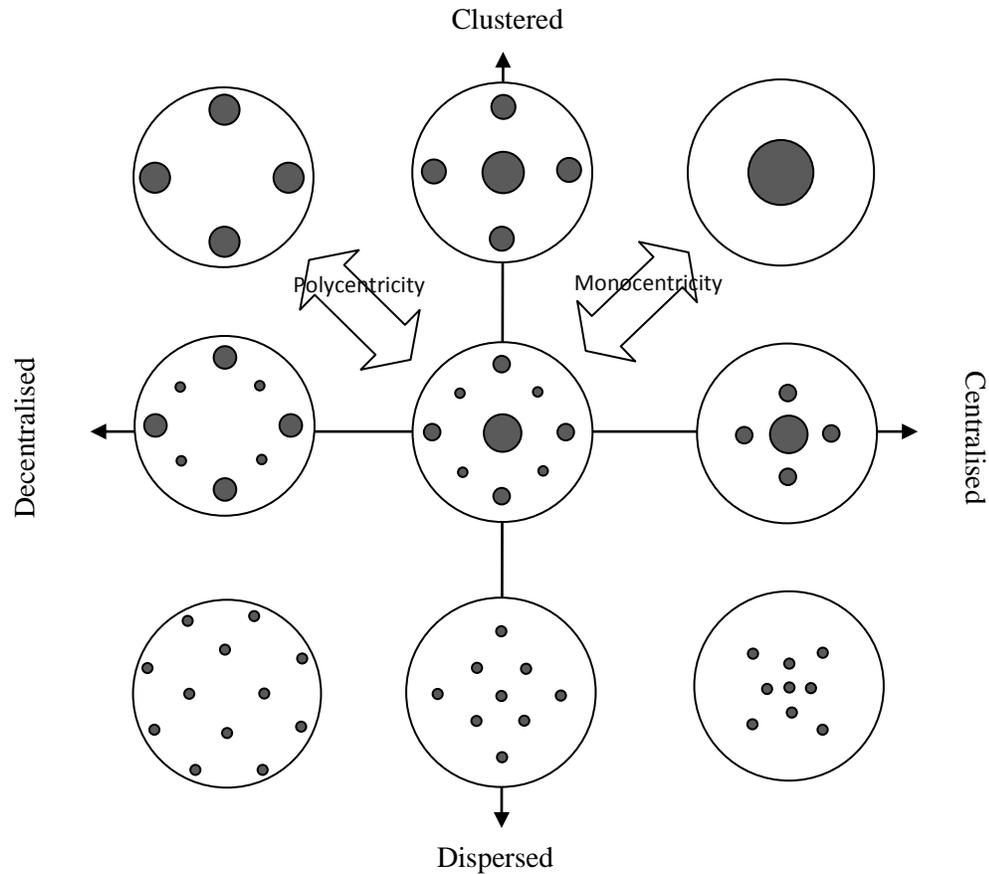
Figure 4.10: Urban-Centre Hierarchy Patterns, Defined by Spatial Clustering and Centralisation

In the centre of the figure we have a pattern of centres corresponding to a standard central-place hierarchy. The models in the four corners represent acute variations in the hierarchy of centres; namely of centralised-clustering, decentralised-clustering, centralised-dispersion and decentralised-dispersion. Monocentricity refers to the spectrum of structures between the central-place hierarchy and the centralised-clustered model. Polycentricity refers to the spectrum of structures between the hierarchical city and decentralised-clustered model. The bottom row of models illustrates dispersed forms lacking spatial clustering, resembling population catchment type distributions.

To apply the above framework empirically we need a statistical measure of spatial concentration. The most commonly used statistic is the Moran's I statistic of spatial autocorrelation, which measures the probability that a distribution is randomly formed. The Moran's I statistic was found to be

relatively ineffective in distinguishing between varied patterns of urban centres shown in Figure 4.10. An alternative global spatial clustering index, the Getis-Ord General G statistic, is shown in Equations 10 and 11. The statistic measures the degree to which high or low values are clustered, based on the product of proximal values (Getis and Ord, 1992). This statistic was found to successfully capture the different urban clustering patterns shown in Figure 4.11 and be largely unaffected by the varying sample sizes of urban functions, thus making it suitable for quantifying agglomeration patterns as applied in Chapter 5.

Equations 10 & 11: Getis-Ord General G Statistic. Source: Getis and Ord (1992).

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} x_i x_j}{\sum_{i=1}^{n} \sum_{j=1}^{n} x_i x_j}$$

Where:

x_i = value of variable at location i

W_{ij} = spatial proximity weights matrix

E [G] = Expected value of G for a random distribution

$$E[G] = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} x_i x_j}{n(n-1)}$$

In summary the terms monocentric and polycentric are scale-dependent terms that describe the relative dominance of centres within a city-region hierarchy or intra-urban network of centres. The combined spatial analysis of clustering and centralisation provides an empirical test of monocentric and polycentric spatial distributions. Monocentricity describes processes of centralised-clustering in the hierarchy of urban centres, whilst polycentricity describes processes of decentralised-clustering. The empirical analysis of these concepts requires statistical measures of spatial concentration, of which the Getis-Ord General G statistic was found to be most effective.

4.7 Techniques for the Analysis of Accessibility and Travel Sustainability

We now turn to spatial analysis techniques for the accessibility and travel pattern indicators. Firstly accessibility measures are detailed, and then we consider the analysis of travel time. Finally the methodology for calculating the intra-metropolitan CO_2 emissions indicator is presented.

4.7.1 Measures of Geographical Accessibility

Geographical accessibility indicators describe the ease of which actors (e.g. residents, firms) can access opportunities (e.g. people, jobs, shops, parks) through transport networks. Accessibility has fundamental relationships with travel demand (see Chapter 3) and urban form (see Chapter 1). Measures of accessibility in urban geographical theory generally consist of two parts: a transportation (or resistance/impedance) element and an attraction (or motivation/activity) element (Handy and Niemeier, 1997), as shown in Equation 4. Accessibility measures are generally composite indices that sum accessibility values from one zone to all other zones. Different forms of the impedance function result in three general classes of accessibility measure: cumulative opportunity measures, gravity-based measures and utility-based measures. Cumulative measures or threshold measures total the opportunities within a given travel cost, for example the total population within 45 minutes travel time. In the cumulative case the impedance function is binary, either being 1 if the opportunity is within the threshold or 0 if it is beyond the threshold. The advantage of cumulative measures is in their simplicity, both for calculation and for communication to stakeholders. On the other hand the arbitrary cut-off value is a poor reflection of travel demand relationships.

Equation 4: General Accessibility Index. Source: Handy and Niemeier (1997).

$$A_i = \sum_{j=1}^{n} S_j \, f(T_{ij})$$

Where:

S_j = Total activity/opportunity within zone j

$f(T_{ij})$ = Impedence function based on the travel cost t between zones i and j

A second group of accessibility measures are gravity measures, which are derived from the gravity model trip-distribution component of the four stage

transportation model. The original introduction of accessibility concepts to geography was based on transferring notions of potential interaction from physics using gravity measures (inspired by the inverse square law of Newtonian Gravitation). In the seminal paper *"How accessibility shapes land use"* Hansen defined accessibility as varying directly with the size of opportunities and inversely with the distances to those opportunities (Hansen, 1959), as shown in Equation 5. The value of *x* represents the distance decay factor, which should be calibrated against empirical data. Various alternatives to the inverse-power function have been substituted, with negative exponential and log-normal functions being common in geographical research (Handy and Niemeier, 1997).

Equation 5: Hansen Accessibility Index. Source: Hansen (1959).

$$A_i = \sum_{j=1}^{n} \frac{S_j}{T_{ij}^x}$$

Where:

S_j = Total activity/opportunity within zone *j*

T_{ij} = travel cost between zones *i* and *j*

x = *distance decay factor*

The third and final class of accessibility measures is based on random utility theory, in which the probability of an individual making a travel choice depends on the utility of that choice relative to the utility of all choices. Accessibility is here defined as the denominator of a multinomial logit model, as shown in Equation 6 (Handy and Niemeier, 1997). Utility based measures are considerably more sophisticated than the other approaches and can be used to calculate monetary values for the costs of changes in accessibility to travellers. Utility measures do however place greater demands on data and analysis and calibration, and are less intuitive for use in planning policy contexts.

Equation 6: Accessibility Utility Measure (Handy and Niemeier, 1997)

$$A_n = \ln \left[\sum_{\forall \in C_n} exp\left(V_{n(C)}\right) \right]$$

Where:

A_n = Accessibility for person n.

C = Specified choiceset for person n.

$V_{n(c)}$ = Temporal and spatial transportation components of indirect utility of choice C for person n.

In addition to the choice of impedance function, there are several other factors to consider in selecting accessibility indicators. These include the type of travel cost measured, the degree of disaggregation, and the choice between origin and destination based measures (discussed previously in Section 3.2.1). Travel cost is typically measured in terms of distance, time or generalised cost (see the next section). More accurate urban travel times should be mode-specific and consider routes through transportation networks. The disaggregation dimensions of accessibility measures include trip-type, transport mode, socio-economic disaggregation, and the disaggregation of the opportunity measure. Thus accessibility measures can vary from very general indicators to the very specific. This research develops journey-to-work accessibility indices, disaggregated by mode, using network travel times and population and employment opportunity measures.

In summary, accessibility is a fundamental concept in geographical analysis, providing the link between urban activities and how they are connected through the transportation system. Thus it is relevant to a host of research areas in land-use transportation interactions, transportation sustainability and economic geography. Even within the urban geography actor-opportunity accessibility measures, there are a wide range of possible indicators, ranging from the simple to fairly complex, and from general to highly disaggregate. This research focuses on journey-to-work measures disaggregated by mode to population and employment opportunities.

4.7.2   Defining Network Travel Time and Travel Cost

From the accessibility discussion above it is clear that the definition of travel cost is a key component of accessibility measures. This research is based on the measurement of travel cost as travel time, using network analysis of transport services and speeds. As the travel accessibility for a car trip is distinct from a public transport/pedestrian/cycle trip, the travel cost functions need to be defined individually for each transport mode. Whilst the measures of network travel times are more sophisticated than basic geographical research using 'crowfly' distances, they do not include other relevant factors such as monetary costs. We consider the limitations of this approach in the discussion.

Travel time is an essential component of the analysis of travel cost. The calculation of accurate urban travel times requires analysing the structure of urban transportation networks and services, in addition to other pertinent network effects such as congestion. The datasets used for the representation of transport networks have been described earlier (Section 4.4.6) and here we discuss analysis techniques to derive travel times from these networks. The basic factors for calculating network speeds by car are shown in Equations 7 and 8 below.

Equations 7, 8: Network Travel Time by Car

$$T_{car} = T_{net} + T_{walk}$$

$$T_{net} = \sum_{i=0}^{n} \frac{L_{length}}{L_{speed}}$$

Where:

T_{car} = travel time by car
T_{net} = In-vehicle travel time
T_{walk} = Walk travel time to car & parking

n = links on road trip route
L_{length} = road link length
L_{speed} = average speed on link

Road network layers define lengths for each link, and the key unknown factor for calculating accurate times is the average speed on each link. A number of sources can be used to estimate speeds on road links, such as road classifications (relating to speed limits) and road capacity data such as number of carriageways. The weakness with these approaches is that congestion is not considered. This is a major shortcoming in a city such as London where demand vastly exceeds road supply and congestion delay is a major component of journey time. This research uses GPS-based transport data to calculate average road speeds on a detailed link-by-link basis for peak travel time (Section 6.1). There is an issue of how accurately link-speed based approaches capture junction delays, and this has not been considered in detail in this research due to a lack of independent calibration data.

The calculation of routes and travel times for public transport journeys is more complex than for private vehicles. Journey components include walk stages, in-vehicle stages and potentially interchange stages, as shown in Equation 9. The calculation of travel times on public transport services can be timetable based (ideally with an additional reliability factor) or alternatively can use distance-based average speed calculations. This research employs a mixed approach

depending on the public transport mode, with average speeds assigned to network links using timetable data (see Section 6.1).

Equations 9: Travel Time by Public Transport

$$T_{pt} = T_{walk} + \sum_{i=0}^{n} \left(T_{wait} + T_{net} + T_{chng} \right)$$

Where:

T_{pt} = travel time for public transport journey
T_{walk} = walk time from origin to first station, and final station to destination
n = public transport services on route
T_{wait} = time waiting for public transport service
T_{net} = time on public transport service
T_{chng} = walk time to interchange services

Once the networks have been constructed and assigned with the costs detailed above then accessibility measures are calculated using algorithms to identify minimum cost routes, in this case minimum time routes. The efficient calculation of shortest network paths is a longstanding problem in mathematics and computer science, with established heuristics including Dijkstra's (1959) algorithm and the A* algorithm (Hart *et al.*, 1968). Network analysis tools are increasingly incorporated into GIS software to integrate spatial data processing and network analysis tasks in the same software environment, and this is the approach used in this research.

Accessibility measures based only on travel time can be criticised for excluding various other factors that influence travel behaviour. This includes the monetary cost of trips, as well as 'softer' factors such as comfort, safety and various personal preferences. Financial costs are typically incorporated in transport models using generalised time / generalised cost as an integrated measure of time and money. Values of time can be disaggregated by activity, with the perceptions of cost varying between modes and journey stage. The development of generalised cost accessibility measures would be a useful future addition to this research. There are however a number of difficulties within the scope of this research for the calculation of generalised costs and their application. A number of central aspects of travel costs are not directly available from data sources, particularly parking costs and public transport fares. Furthermore the importance of money in travel behaviour is highly dependent on income, thus a move to generalised cost analysis would also require the socio-economic

disaggregation of the analysis in this research to achieve any additional insights from generalised cost. Similarly socio-economic disaggregation is also essential for softer behavioural factors to be included. The approach used in this research uses socio-economic characteristics as independent variables in the model rather than as the basis of disaggregation (see Chapter 6). The focus here is on accessibility and travel flow relationships across an entire city-region, with high levels of spatial rather than socio-economic disaggregation.

4.7.3   The Intra-Urban Analysis of Travel Flows and CO_2 Emissions

Alongside the accessibility and travel cost measures discussed above it is vital to analyse data on actual urban travel patterns. The combined analysis of flow and travel cost matrices can be used to explore relationships between accessibility and travel flows, i.e. between potential and actual interactions. The analysis of travel data is the basis of measuring travel sustainability, which in this research is the CO_2 emissions indicator. This allows the sustainability impacts of travel patterns to be quantified and relationships analysed.

Aggregate travel pattern data is based on a matrix structure defining flows between origin and destination zones. In the context of the UK census, travel costs such as travel distance and time are not included in the source data, and need to be calculated using the network analysis methods described in the previous sub-section. As the number of zones increases (with generally thousands of zones needed for meso-scale city-region analysis) the number of flows increases exponentially. Therefore techniques to summarise the properties of matrices and understand general patterns are useful. This could involve macro-city scale analysis where a single value for an entire city is calculated (see Sub-Section 3.3.3). This approach is useful for analysing city dynamics as a reduced number of headline indicators are calculated (Frost and Spence, 2008), though it in unsuitable where intra-urban spatial patterns are the focus. For sub-regional analysis Plane (1995) proposes collapsing the matrix into a three-fold inner-city, outer-city and hinterland structure, leaving a greatly reduced 3x3 matrix. A version of this sub-region technique is calculated for mode-choice in the London region in Section 6.2. The problem with this technique is that it is strongly affected by MAUP effects, and it assumes a

monocentric structure, thus cannot adequately explore the sub-centres and polycentric forms that are the main focus of this research.

Instead this research is based on calculating the properties of flows for the entire city-region matrix. The advantage of this approach is that it makes no prior assumptions about urban structure, and is highly comprehensive with all the city-region flows analysed (flows with external origins/destinations should be included as well). The challenge for this approach is the computational overhead, and thus the GIS software and database technologies described earlier in this chapter are an essential prerequisite for this method. The computational demands depend on the size of the matrix, which in turn depends on the study extent and zonation selected. The only two available 2001 census zonations sufficiently fine-grained to identify urban sub-centres in the UK are wards (approximate residential population 12,000) and output areas (approximate residential population 300). As the extent of this study is relatively large, the corresponding matrices are very large, with the ward matrix containing approximately 3 million values and the output area matrix containing over 4 billion values! Whilst the majority of the values in these matrices are zero (about 15% of potential flows are greater than zero in the study area), the size of the output area matrix was found to be infeasible for current desktop GIS software. Therefore the ward zonation is used as the basis of the travel analysis in this research. This scale proves to be sufficient in identifying detailed intra-urban patterns (see Chapter 6). Note also that some key variables such as employment class have not been released for the UK census at output area scale, which would also be problematic for the relationships analysed in this research.

Once the matrices for the study area have been completed- including relevant mode-choice and socio-economic data, and the calculation of mode-specific travel time and distance for each flow- the sustainability properties of each flow can be estimated. The advantage of composite indicators such as CO_2 emissions and energy use is that they integrate mode-choice and distance patterns into a single measure. Furthermore CO_2 and energy concerns are ultimately central to sustainability policy. The method used here is to multiply the distance travelled by each mode by a mode-specific emissions factor modelled by the UK

government. Similar approaches has been used in existing studies (Banister *et al.*, 1997; Frost and Spence, 2008) and the novelty in this research is the intra-urban scale and level of detail in the network routing analysis, as well as a CO_2 rather than an energy focus. The emission factors used are shown in Figure 4.11. These are estimates of the direct emissions resulting from a trip, not including less specific indirect emissions from vehicle manufacture and infrastructure construction (note that the direct/indirect distinction is more problematic for public transport networks as discussed below).
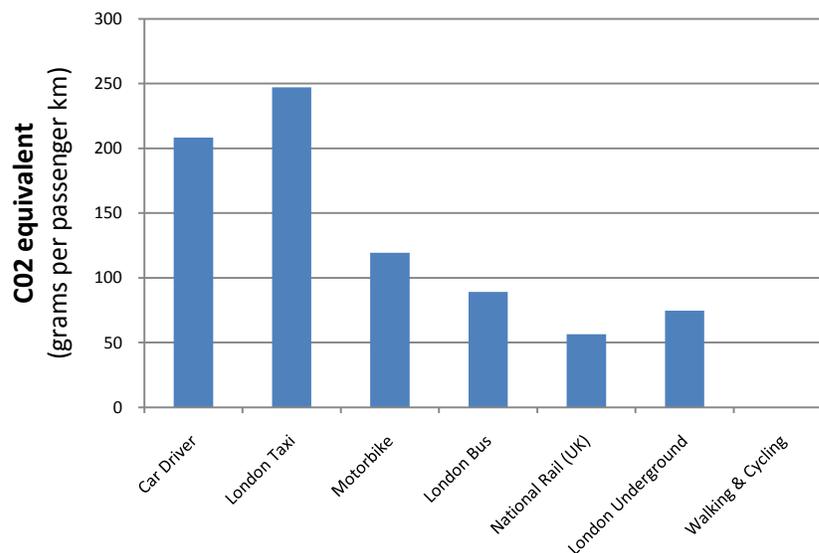
Figure 4.11: Estimates of Carbon Dioxide Emissions Per-Passenger-km by Private and Public Transport Modes (London values shown where available). Source: DEFRA (2010).

DEFRA has developed a detailed methodology for producing the above emission coefficients including profiling of the UK vehicle fleet; empirical analysis of typical road conditions and driving behaviour; integrating the results of public transport models from National Rail and Transport for London; including emissions resulting from the production of fuels (e.g. crude-oil to petrol); and additionally including CO_2 equivalent emissions from other greenhouse gases such as methane and carbon monoxide (DEFRA 2010). The challenges for this distance based mode-coefficient methodology relate to the degree to which spatial and temporal patterns diverge from these average values, particularly for key variables such as vehicle occupancy. For private cars, emissions depend on such factors as the engine size/car model, driving

speed/degree of congestion, and number of passengers. The method used here assumes that the car properties are evenly dispersed from the mean across the study area. For occupancy, the UK census records whether car users are car drivers or passengers. Thus we can calculate the average occupancy of vehicles in the study area, and calculate different average occupancies for car driver and car passenger trips (i.e. occupancy must be at least 2 for passenger trips). For congestion effects, a logical approach would be to calculate carbon emissions on a link-by-link basis in the network analysis stage. This technique would require the micro-level calibration of relationships between CO_2 emissions and link-based average speeds, which is unfortunately beyond the scope of this current work, but should be a priority for future research.

Public transport trip emissions are also affected by similar issues of spatial and temporal disaggregation. DEFRA provide data on London-specific tube, bus and taxi emissions (DEFRA 2010), which allows a basic level of spatial disaggregation to the London study area. National rail figures for London are not available, and UK figures have been used here. The issue is that occupancy is likely to be higher for London services and so public transport emissions may be over-predicted. The occupancy of public transport varies temporally between peak and off-peak services, with commuting journeys taking place during peak times, and only average business transport values are available through the DEFRA statistics used here. Using average occupancy means that per-capita carbon emission estimates for public transport are likely to be over-estimated. Public transport is problematic in a wider sense for this methodology as emissions are less 'journey-specific' and could be considered as a product of the public transport system as a whole. The relationship between public transport supply and demand is less direct and immediate than private transport. Yet public transport is demand responsive in the longer term, and the alternative of ignoring carbon emissions from public transport would be highly misleading for policy.

In summary, the meso-scale city region analysis of travel patterns involves handling large matrices with potentially millions of flows, and subsequently GIS technologies are essential in calculating indicators based on these matrices.

Composite indicators such as CO_2 emissions and energy use integrate trends in mode-choice and travel distances, and provide data directly relevant to policy. The emission coefficients are central to these indicator calculations. This research makes significant progress in spatial disaggregated analysis of intra-urban travel flows, but errors remain in the spatial and temporal disaggregation of emission coefficients regarding factors such as occupancy and congestion. Addressing these issues should be a priority for future research in this field.

4.8   Chapter Conclusions

This chapter has addressed Research Aim 3, which is to develop the methodology for the intra-metropolitan analysis of employment geography, urban structure and travel patterns. Data and methods to analyse employment geography, the built-environment, accessibility and travel sustainability have been detailed, and these methods are applied to the study area of the London region in the next two chapters of this thesis. Geographical analysis typically involves a trade-off between study extent and level-of-detail, but improvements in data extent and availability, in tandem with the analysis and visualisation capabilities of GIS, are enabling this trade-off to be overcome with the linking of extensive and intensive analysis. A meso-scale intra-metropolitan analysis, which is at a regional extent and is relatively fine-scale, has been advocated here to provide an appropriate balance for the study of city-region structure. Several methodological hurdles remain however, and a series of methodological innovations have been proposed to enable the intra-metropolitan spatial analysis of cities to be effective. These are the detailed analysis of business survey data for the fine-scale measurement employment geography; the inclusion of real-estate data in geographical analysis to allow property market processes and urban development to be analysed; and more accurate accessibility measures based on the network analysis of detailed transport infrastructure and timetable data. Finally a CO_2 travel emissions methodology has been developed in a format that can be calculated for millions of trips in a city-region. This approach of including the entire trip matrix at an intensive zonal scale allows comprehensive intra-metropolitan analysis which is capable of identifying trends connected to decentralised, polycentric and monocentric forms. This is opposed to the more commonly applied aggregate approaches that mask intra-urban variation. GIS tools are an essential prerequisite to handle the computational demands of this approach.

The urban structure analysis methodology is very demanding in terms of data, and there are some gaps in data availability. These can be minimised by drawing on multiple data sources to allow dynamic analysis and link socio-economic and built-environment geographies. For the study area of London there are issues regarding the availability of detailed real-estate data for the

wider region which restricts the real-estate analysis in Chapter 5. There are also data gaps in the travel pattern indicators. The UK census does not contain information on travel distances and times, or more complex sustainability indicators such as CO_2 emissions. A methodology to derive these travel cost measures using GIS analysis has been detailed. The main shortcoming in the travel data is that it is restricted to journey-to-work travel in 2001. The methodology could be applied to any time period or trip type where data is available, but the analysis of the London region travel in this research is restricted to journey-to-work.

The second aim of this chapter (Research Aim 4) was to provide a methodology for the empirical analysis of monocentric and polycentric forms. We concluded that monocentricity and polycentricity are scale-dependent relative terms that describe patterns of dominance within an intra-urban hierarchy or network of centres (similar to central place theory described in Chapter 2). The technique developed to identify these forms uses a combination of centralisation and clustering spatial statistics to provide a transparent method of classifying urban forms. These methods are applied in the London context in the next Chapter.

Chapter 5

The Economic Geography and Development of the London Region

Based on the theoretical discussion of urban physical form, socio-economic structure and sustainable travel in Chapters 1-3, and the empirical methodology described in Chapter 4, we now turn to applying the theory and methods to the case study of the London Region. The overall aim (Research Aim 5i) is to assess the spatial structure of economic activities in London at an intra-metropolitan scale, and assess to what extent these activities can be considered polycentric. This includes analysing the dynamics of economic activity and how future urban form is evolving. This chapter has a strong economic and employment focus as firm location and agglomeration trends have a central role in shaping urban form and travel patterns, yet have not been given sufficient attention in sustainable travel research.

There are three main sections to the chapter. Section 5.1 provides a general introduction to the study area of London, its development, socio-economic context and relationship with the wider South East region. Then in Section 5.2 the economic geography of the London region is analysed, considering the location of employment and its growth, decline and specialisation. This employment perspective is complemented by a real-estate analysis in Section 5.3 which provides a supply side approach to employment geography and highlights where urban development is taking place. These two perspectives of employment and real-estate geographies are shown to be linked through property markets.

5.1 London and the South East Region

This section provides a geographical and historical context to the study area of London: its growth, transport networks, administrative structure and relationships with the wider region of the South East.

5.1.1 Historic Growth and Decline in London

Urban cycles of creative destruction (see Chapter 1) are spectacularly evident in the history of London. London has a long and complex history as a centre of political power, trade and culture, beginning with its inception during Roman occupation nearly two millennia ago. We focus the discussion here on the 19th and 20th centuries, which have to a large extent shaped the contemporary form of the London region. In these periods London has grown dramatically in physical terms, experienced widespread economic transformations.

Greater London is comprised of many linked historic settlements. These settlements were historically independent cities and towns in their own right, and now form the basis of London's local government structure- the borough councils, shown in Figure 5.1.
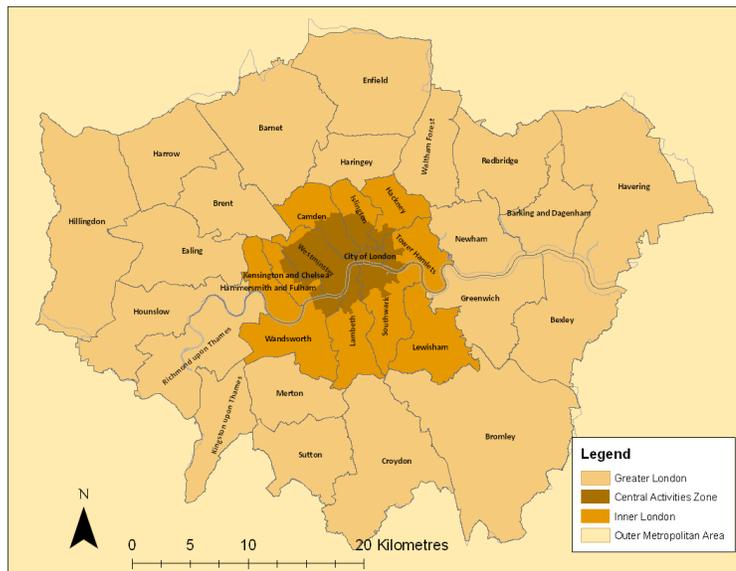
Figure 5.1: Greater London Boroughs. Data Source: Greater London Authority (2004).
Note the planning definitions of the Central Activities Zone and Inner London
have shifted between versions of the London Plan.

The most prominent authorities are the two central boroughs of the City of London, the original roman settlement and now London's financial hub, and Westminster, the seat of national political power. Adjacent to the City and Westminster, the Inner City generally urbanised during 19th century. The Outer London boroughs did not become densely populated until rapid suburbanisation began in the 20th century. The historic integration of smaller settlements into Greater London has given rise to a hierarchical spatial pattern of centres, leading to the characterisation of London as a 'city of villages'.

The growth of Greater London can be explored through historic population trends, as shown in Figure 5.2. The 19th century saw London's population rise nearly six-fold, from 1.1 million to 6.5 million people. This growth trend continued to a peak of 8.6 million in 1939. Severe industrial decline followed the Second World War, and London's population fell to a post-war low of 6.4 million in 1991. In the last twenty years this population decline has reversed, with economic growth bringing international and national in-migration. Note the population trend closely follows New York's (discussed earlier in Figure 1.3) emphasising how post-industrial recovery is linked to world city status. Future population projections are for London's growth trend to continue, although uncertainty about this has increased following the recent financial crisis and economic recession.
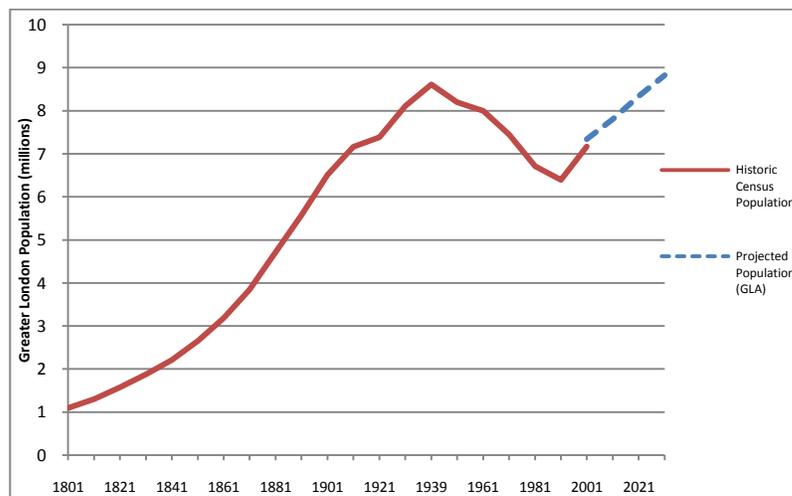
Figure 5.2: London's Historic and Projected Population Graph.
Data Source: Greater London Authority (2008).

This historical population change can also be examined in map form as shown in Figure 5.3. Victorian London is largely confined to the Inner City, with over six million people living at extremely high densities of up to 400 residents per hectare in 1901. Early suburbanisation trends can be seen in the 1901 map, and over the next fifty years a dramatic decentralisation to Outer London occurred, linked to public transport expansion (described in the next sub-section).
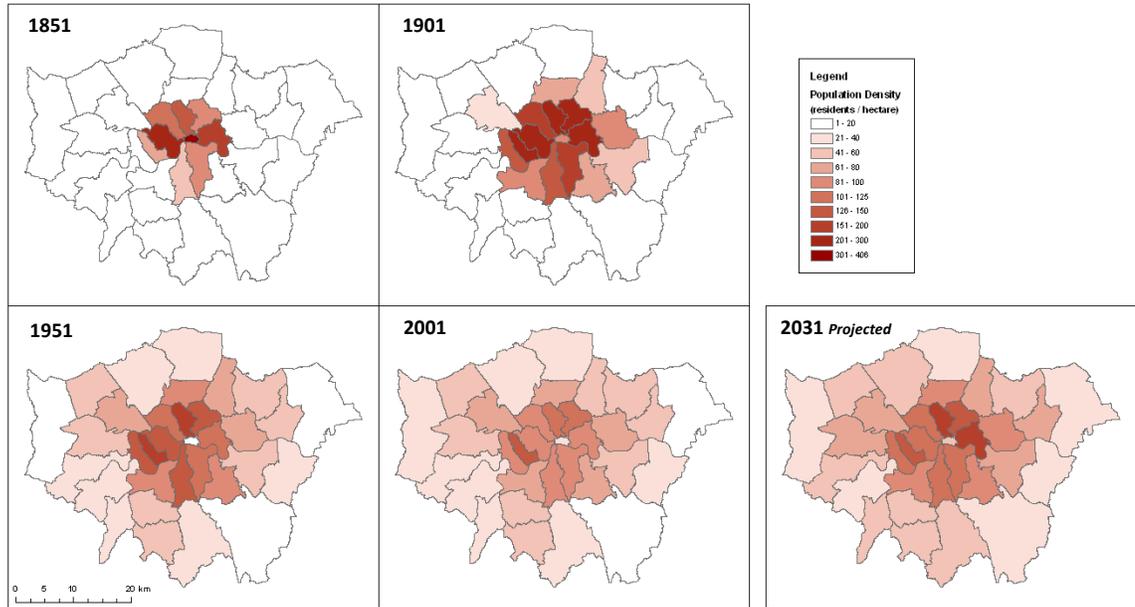
Figure 5.3: London's Historic and Projected Population Density Maps.
Data Source: Greater London Authority (2008).

The second half of the 20th century appears to be relatively stable in Outer London, whilst Inner London experiences continuing population decline. Much of the suburban change during this period occurs beyond Greater London with growth in the wider South East region, particularly through New Towns. Finally the projected population distribution for 2031 is based on increased densities across Greater London, with a particular focus on Inner London. Note that while central residential densities are increasing, they are predicted to remain around half the historic densities of 1901. Employment densities on the other hand are likely to be higher than 1901 (there is a lack of historic data to explore this issue).

5.1.2   The Development of London's Transportation Networks

The dramatic population growth and suburbanisation trends described above are closely tied to transport network development. London's transport network geography has guided and constrained the city, with public transport networks central to growth during the 19th and first half of the 20th century. The move towards automobile transport occurred in the mid-to-late 20th century after London's urban form is largely established, making London traditionally a radial monocentric city (as described in Chapter 1). The particular history of London's development has resulted in an extensive and somewhat idiosyncratic multimodal transportation infrastructure.

Railways first arrived in London in 1836, with the majority of initial developments being intercity rather than suburban in nature (Levinson, 2008). The 1846 Royal Commission on Railway Termini prevented train lines entering Central London, resulting in a ring of disconnected stations, and this stimulated a market for inter-connections and the development of the underground (Levinson, 2008). Both surface rail and underground networks expanded together producing both competition and a degree of complementarity between these modes, as shown in Figure 6.1. Transportation development played a significant role in suburban expansion, with railway companies forming business relationships with property developers and in some cases acting as property developers themselves. The growth of the underground network continued into the mid-20th century when the network reached a comparable level to the present day.

There are major spatial discontinuities in London's public transport coverage, notably the absence of the underground in most of South London, linked to development processes and the profit motive. The railways in South London had fewer opportunities for long haul destinations and developers focussed on suburban connections, thus deterring future underground development (Levinson, 2008). Furthermore the geology of South London has been argued to be less favourable for the underground. Other areas of poor underground service include Hackney and east along the Thames (until the massive public investment programme in Docklands in the late 20th century), indicating that less affluent areas had weaker public transport services.

Figure 5.4: The Evolution of London's Public Transportation System.
Data Sourcing and Visualisation by Nexus Research Group 2010.

The radial public transport network contrasts with the road network. London's current street pattern is a result of layers of overlapping historical development, with Central London retaining routes from Roman and medieval periods, Inner London combining areas of Georgian and Victorian development, and suburban London developing through waves of expansion continuing throughout the 20th century based around historic settlements. The reorientation of roads towards motorised private transport did not take place until the second half of the 20th century with the development of an arterial road network, as promoted by the influential Buchanan (1963) Traffic in Towns report, and the early construction of the motorway network for higher speed intercity travel. Nine radial motorways are linked to London, with the oldest being the M1 opened in 1959,

as shown in Figure 5.5. Few motorways penetrate Greater London itself, and the subsequent lack of intra-urban motorcar accessibility and need to connect existing motorways provided the rationale for the development of the M25 orbital motorway. The idea was first proposed in the early 20th century yet was not completed until 1986. The London orbital has been struggling to meet demand from its inception and has undergone several phases of capacity expansion.
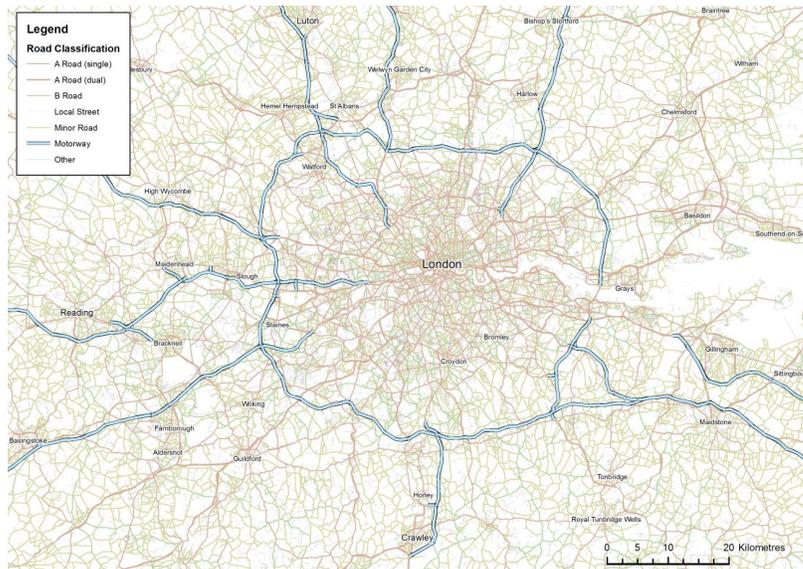
Figure 5.5: London Road and Motorway Network. Data Source: Ordnance Survey (2007b).

It is clear from the mapping of London's transport network infrastructure that the accessibility facilitated by public and private modes contrasts strongly, as is typical for radial network cities (see Section 1.1). Overall within Greater London and particularly Inner London there is a dense radial multi-modal public transport network while beyond Greater London public transport is much sparser. In contrast Greater London suffers from a congested low capacity road network, while beyond Greater London there are extensive motorway links. These variations underlie London's contrasting patterns in accessibility, which are analysed in detail in Chapter 6.

5.1.3 Structural Economic Change and Social Polarisation

London has been at the sharp end of the dramatic socio-economic transformation over the last half century from a manufacturing-based economy to a post-

industrial information, service and global business economy. These comprehensive changes have had both positive and negative effects in creating new economic and social urban orders, class divisions, and transforming economic production spaces. These changes also have a distinct spatial geography within Greater London, with the effects being highly spatially uneven.

The fundamental factor driving change in London's employment structure in the last three decades of the 20th century was the gain of approximately 600,000 jobs in business services and the loss of 600,000 jobs in manufacturing (Greater London Authority, 2004). In the decade 1991 to 2001 London gained nearly half a million jobs overall to a total of 3.8 million, overwhelmingly in business and other services as shown in Figure 5.6 (Greater London Authority, 2007a). The expansion in non-business services has been led by leisure and people-orientated services, boosted by increases in tourism. Considering the very high profile nature of financial services, the number of employees directly involved in financial activities is relatively small, but financial activities are typically high value and are linked to the wider business service growth (see producer services discussion in Sub-Section 1.2.1). The deregulation of financial markets in the late 1980's is commonly cited as a key factor in the dramatic business and financial service expansion (Wharf, 1995), with minimal regulation also a central cause of the current economic crisis (Stiglitz, 2010).

Figure 5.6: Employment change by broad sectors, 1973-2001.
Source: Greater London Authority (2004).

The dramatic structural economic change depicted in Figure 5.6 has resulted in a spatially uneven distribution of employment gains and losses. Centuries old social polarisation and class divisions have been reinforced through this structural change. The traditional locations of industrial activities in London are mainly in the Inner City and East London, and formerly working class populations in these areas have been severely affected by unemployment from the loss of skilled industrial jobs. This can be seen in the distribution of the UK government index of multiple deprivation shown in Figure 5.7. Note that Inner and East London have also been the main location for immigrant populations into London, many of whom are in more deprived socio-economic groups and have sought employment in the expanding service sectors.

Figure 5.7: Index of Multiple Deprivation. Source: Office of the Deputy Prime Minister (2004).

5.1.4   The Greater London Authority and the London Plan

In the 1980's when London's population and economy began to reverse the trend of four decades of decline, the city faced massive planning challenges relating to unemployment and industrial regeneration, housing shortages, public transportation, commercial property and the public realm. The Labour dominated regional government of London, the Greater London Council, was dissolved by the Conservative national government in 1986. This left a void in co-ordinated metropolitan planning for London, and problems such as underinvestment in housing and public transport infrastructure were subsequently exacerbated over the next decade. Regional government was revived by the Labour administration

elected in 1997. The Greater London Authority (GLA) was established in 2000, covering the 33 local councils (shown earlier in Figure 5.1). The authority consists of a directly elected Mayor and a separately elected Assembly. The GLA's purpose is to provide strategic government for London, including producing a Spatial Development Strategy, commonly referred to as the London Plan, setting a social, economic and environmental framework for future development. Planning decisions from the borough councils must by law comply with the London Plan.

The first GLA London Plan was published in 2004. The key development aims of the plan included: raising densities and concentrating development on brownfield land, in line with compact-city planning approaches; upgrading public transport infrastructure (overwhelmingly on radial routes) and phasing development with public transport capacity and accessibility; addressing supply side issues particularly commercial floorspace and housing; and prioritising development and regeneration towards socially deprived areas, mainly in East London (Greater London Authority, 2004). These policies are summarised in the London Plan Key Diagram shown in Figure 5.8.

Figure 5.8: London Plan Key Diagram. Source: Greater London Authority (2004).

To concentrate development on brownfield land and enable integration with public transport, the policy instruments of Opportunity Areas and Intensification Areas were developed. These are sites judged to be suitable for major employment and housing development. As shown in Figure 5.9, these are overwhelmingly located within Inner London and East London. The area of the Isle of Dogs and the Royal Docks (collectively known as Docklands) had already undergone large scale industrial regeneration for two decades at the time of the first London Plan. The high profile development of Canary Wharf created a major new business centre in Inner East London. Whilst eventually considered a commercial success, the experience of Docklands regeneration highlighted many development pitfalls, as a lack of transport infrastructure initially stalled the arrival of new tenants and the private developer went bust in the early 1990's property recession. Social inequality critiques have also been made with a lack of affordable housing and minimal connections to local communities (Foster, 1999).

Figure 5.9: Opportunity Areas and Indicative Development Capacity.
Source: Greater London Authority (2004).

Investment in public transport has been a priority policy of the GLA in the last decade. This has included new capacity and upgrading of the underground, the bus network and mainline rail. A congestion charge was introduced in 2003, charging private vehicles to enter Central London, with the proceeds invested in public transport. Two significant new rail lines are shown in the Key Diagram (Figure 5.8). These are the high speed Channel Tunnel Rail Link, which was completed in 2007, and provide a direct high speed services to continental

Europe and the Olympic site at Stratford. The second major new rail line running East-West is known as 'Crossrail' and is intended to link Central London with the corridor of development in East London and with Heathrow Airport. Crossrail has been given backing by central government and has begun initial construction, though the high cost (currently estimated at £13 billion) is controversial given the current economic climate.

5.1.5 Greater London and the Wider South East Region

As this research has advocated the necessity of a regional perspective on cities, and measures the degree of regional polycentricity in London's economic activities, then the relationship between Greater London and the wider region of the South East is a key issue. The Greater South East comprises an extensive area of England with a network of towns and cities, all of a relatively modest size compared to London, as shown in Figure 5.10. These towns include a mix of historic settlements and 20th century New Towns, with a particular concentration within 50km or so of London within the informal boundary known as the Outer Metropolitan Area. Indeed there is no definitive boundary of the South East region, and we return to this issue in Section 6.1.
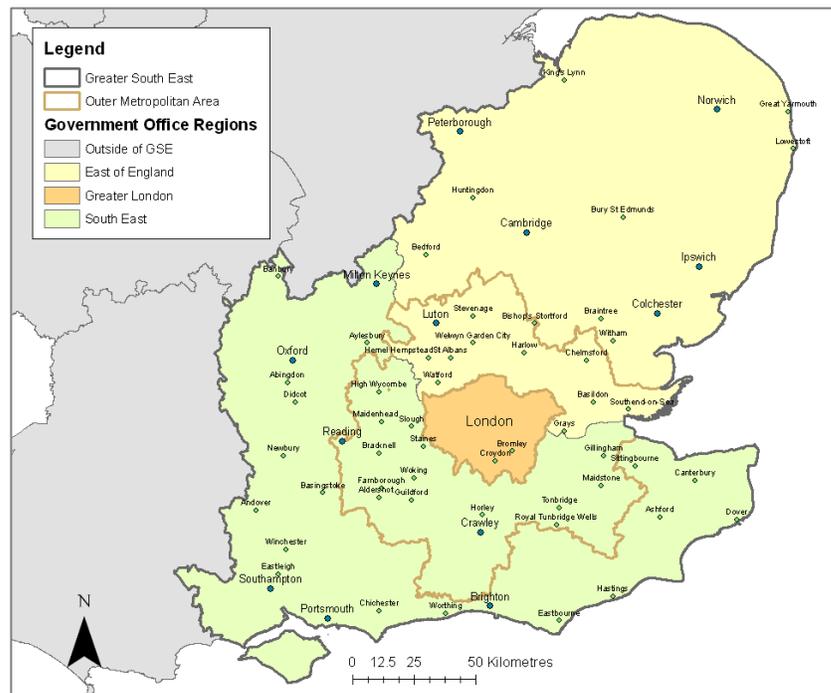
Figure 5.10: The Greater South East Region and Major Settlements.

In the urban theory discussion in Chapter 1 it was stated that improved accessibility and increased economic specialisations were creating more extensive urban regions with more frequent regional interactions. This can be tested for the study area by looking at the dynamics of commuting interactions between London and the surrounding region, as shown in Table 5.1. In 1991 822,000 journey-to-work trips crossing the Greater London boundary, and this increased to 959,000 trips by 2001. Early data indicates that this figure has increased by a further 150,000 trips in the last decade (TfL, 2010). This trend provides a strong indication that the urban theory of increased regional interactions is occurring in London, and this confirms the relevance of the regional approach taken in this research. The close links across the South East in terms of business connections and travel patterns has led to the characterisation of the South East by some researchers as a polycentric mega-city region (Hall and Pain, 2006). We examine this characterisation in terms of employment geography throughout this Chapter. Note also that increased regional journey-to-work patterns will also have sustainability consequences, as explored in Chapter 6.

Table 5.1: Journey-to-Work Interactions Across the Greater London Boundary.
Data Source: Greater London Authority (2007a).

	1991	2001	Change	% Change
Population working in London and living outside of London	672,730	722,539	49,809	7
Population working outside of London and living in London	149,820	236,018	86,198	58

In terms of planning governance, there are two adjacent Government Office Regions to Greater London, the South East region and East of England region. These regions have no administrative body equivalent to the GLA and regional planning is much weaker, with decision-making residing at county and district level local government. Growth in the wider South East region is planned to be directed towards development corridors as illustrated in Figure 5.11. Note that airports play key roles as growth hubs in many of these growth corridors, with Heathrow in the Western Wedge, Gatwick in the Crawley corridor, Stansted in the Cambridge corridor, and Luton in the North-West corridor. Ashford is connected to the high speed continental rail link, and has been selected as a

growth hub. The Thames Gateway is a long-running ambitious plan to link urban regeneration in East London with wider regional growth along the Thames Estuary. The plan is housing led, but also includes business and industrial facilities, and upgraded transportation infrastructure. The recent sharp decline in property prices has inevitably slowed this development.

Figure 5.11: Growth Areas in the South East Region. Source: Greater London Authority (2009).

5.1.6   Summary

The current spatial structure of London has been forged through capitalist cycles of urban growth and decline. Over the last 150 years extensive suburbanisation has occurred based largely on public transport networks and the integration of older towns and village patterns, producing the general urban form that exists today. The 20th century history of London is dominated by dramatic industrial decline post-WWII, offset by booming business and financial services since the 1980's. Recent decades have also seen growth and greater travel interaction with the wider South East region, confirming the theory of increasing urban regional integration and the appropriateness of the regional analysis undertaken in this research.

5.2   The Geography of Economic Activity in London

This section examines the spatial structure of employment in London, in terms of employment centres, growth and decline and specialisation. This analysis is undertaken at an intra-metropolitan scale, allowing the identification intra-urban and regional processes. These processes include finer scale intra-urban processes of specialisation and agglomeration that differentiate between activity centres. These types of specialised multi-centric patterns underpin polycentric forms (see Chapter 1) and are also likely to be connected to journey-to-work variation (explored in Chapter 6). The approach also allows wider regional patterns to be explored, to examine if significant activity and specialisation is occurring beyond the Greater London boundary. These processes are dynamic, and the analysis incorporates employment dynamics, examining which sectors are growing and driving future urban forms.

We begin with an overview of the employment sectors that London specialises in in 5.2.1, and identify which sectors have shown the most dramatic growth and decline in recent decades. We then move to analysing the geography of aggregate employment in Greater London and the wider region in 5.2.2, including employment dynamics in 5.2.3. Next the important issue of employment specialisation is explored. The intra-metropolitan analysis of employment specialisation is a new approach and so different empirical measures are tested to explore their effectiveness. This includes occupational class data in 5.2.4 and detailed industrial sector analysis in 5.2.5.

5.2.1   Sectoral Overview of the London Economy

Here we examine the economic activities that London specialises in at an aggregate level, and consider recent employment dynamics. The analysis is based on the Annual Business Index, which is an annual survey of 10% of firms. To overcome the problem of the small sample size, results from multiple survey years have been averaged. The two periods studied are 1998-2002 inclusive, and 2006-2008 inclusive (2008 is the most recent survey data currently available at the time of writing). A broad level of sectoral disaggregation is selected, using 2-digit SICs (the same data at a 4-digit SIC level is presented in Appendix B). The sectors with the greatest absolute numbers of employees in London are public

service and administration activities. Greater insight into economic structure can be gained by comparing relative concentrations of industries using location quotients. Sectors with the highest location quotients are shown in Table 5.2. London's major specialisations are financial services, business services, transport, media industries, public administration, and tourism related activities (Gordon and McCann, 2000; Graham, 2003). Other more modest specialisations include information technology, retail and wholesaling. The 4-digit SIC data supports these trends, with even more extreme specialisations in banking and media sectors apparent (see Appendix B). Significant differences can be seen in the location quotients for London and the South East, indicating distinct functional roles for London and the surrounding region. It is also instructive to highlight the complete absence of manufacturing activities from the table (printing and photographic activities appear at 4-digit level).

Table 5.2: London Highest Sector Concentrations 2 Digit SIC Level, 1998-2002 Average. Data Source: Annual Business Index 1998-2002 (ONS, 2010c).

SIC	Industry	London Total	London Loc. Quotient	Greater South East LQ
67	Auxiliary financial intermediation	98,454	2.66	1.61
62	Air transport	36,038	2.59	2.05
65	Financial intermediation	196,590	2.04	1.27
22	Publishing,printing,reprod. recorded media	96,107	1.73	1.32
74	Other business activities	709,432	1.66	1.30
70	Real-estate activities	88,928	1.65	1.33
92	Recreational, cultural and sporting	160,501	1.58	1.19
72	Computing and related activities	107,651	1.50	1.53
63	Supporting/auxiliary transport	82,821	1.40	1.27
64	Post and telecommunications	108,631	1.33	1.20
91	Activities membership organisations	41,221	1.25	0.99
61	Water transport	3,072	1.19	1.52
66	Insurance and pension funding	39,215	1.10	1.23
55	Hotels and restaurants	269,294	1.05	0.99
75	Public admin/defence	214,882	1.02	0.91
51	Wholesale trade/commission trade	183,221	1.02	1.12
60	Land transport; transport via pipelines	80,890	1.01	0.92

Next we examine which sectors have displayed the largest recent changes in employment. The two periods compared are average totals for 1998-2002 (as above) and for 2006-2008. The sectors displaying the greatest absolute growth are shown in Table 5.3 and the greatest decline in Table 5.4 (again 4-digit SIC data is provided in Appendix B). The most spectacular expansion is in "Other

Table 5.3: London Growing Sectors 2 Digit SIC Level 2000-2007.
Data Source: Annual Business Index 1998-2002, 2006-2008 (ONS, 2010c).

SIC	Industry	London Total 2000	London Total 2007	Employ. Change	Loc. Quot. 2007
74	Other business activities	709,432	824,609	115,177	1.56
85	Health and social work	320,629	386,709	66,080	0.77
80	Education	255,006	300,782	45,776	0.80
55	Hotels and restaurants	269,294	292,783	23,489	1.06
67	Auxiliary financial intermediation	98,454	117,153	18,698	2.57
92	Recreational, cultural and sporting	160,501	174,187	13,686	1.50
75	Public admin/defence	214,882	226,803	11,922	1.01
62	Air transport	36,038	46,338	10,301	3.36
70	Real-estate activities	88,928	99,090	10,162	1.39
72	Computing and related activities	107,651	116,710	9,059	1.42
91	Activities membership organisations	41,221	49,083	7,862	1.51
63	Auxiliary transport	82,821	88,354	5,533	1.28
93	Other service activities	47,612	50,548	2,936	1.02
73	Research and development	13,792	16,083	2,290	0.94

Table 5.4: London Declining Sectors 2 Digit SIC Level 2000-2007.
Data Source: Annual Business Index 1998-2002, 2006-2008 (ONS, 2010c).

SIC	Industry	London Total 2000	London Total 2007	Employ. Change	Loc. Quot. 2007
51	Wholesale trade/commission trade	183,221	154,963	-28,258	0.91
64	Post and telecommunications	108,631	87,475	-21,156	1.21
22	Publishing, printing	96,107	76,281	-19,826	1.71
65	Financial intermediation	196,590	181,899	-14,691	2
45	Construction	134,537	120,768	-13,769	0.62
66	Insurance and pension funding	39,215	25,612	-13,603	0.99
50	Sale, mainten. Of motor vehicles	54,103	41,596	-12,506	0.5
24	Manuf chemicals	16,460	7,274	-9,186	0.27
18	Manuf apparel, dressing	13,281	5,312	-7,969	1.24
28	Manuf metal products	16,620	9,584	-7,035	0.2
36	Manuf furniture	14,355	8,420	-5,935	0.38
31	Manuf electrical machinery	10,132	4,828	-5,304	0.29
29	Manuf machinery and equipment	13,047	7,828	-5,218	0.19
34	Manuf motor vehicles	10,842	5,837	-5,005	0.24
52	Retail trade	375,989	371,159	-4,831	0.87
71	Renting equipment	21,216	17,300	-3,916	0.73
15	Manuf food products	30,279	26,806	-3,472	0.45
33	Manuf medical	7,812	4,471	-3,341	0.26
25	Manuf rubber and plastic	9,874	6,535	-3,339	0.24
21	Manuf pulp, paper	4,684	1,630	-3,055	0.17
32	Manuf radio, tv/com.	5,224	2,433	-2,791	0.28

business activities", which includes management consultancy, legal, accountancy, advertising, architecture, and labour recruitment, confirming the discussion in Section 1.2 which highlighted the importance of producer services. Other expanding sectors include a range of public service, tourism and air transport activities, again linked to London's world city role. In contrast sectors in decline are dominated by manufacturing, many of which are effectively disappearing from London altogether. Manufacturing decline is not however the only pattern of employment loss. A number of service sectors also display high levels of decline, including sectors in banking, IT and insurance. This is evidence of restructuring occurring in a number of service sectors, with some lower value activities moving to cheaper locations and/or being made less staff intensive (e.g. data processing, printing, life insurance). Generally increasing international competition is likely creating a more volatile business environment, with simultaneous expansion and decline within relatively narrow service specialisations. Overall the processes of creative destruction discussed in Chapter 1 continue apace, with the London economy displaying high degrees of specialisation and volatility.

It is important to question whether the growth patterns between 2000 and 2008 will be representative of future economic change. In late 2007 a near catastrophic economic crisis began in the financial sector, leading to unprecedented state intervention in the economy (Stiglitz, 2010). Future growth in financial services is likely to be greatly reduced, or potentially negative, while high levels of public debt are currently translating into significant public sector job cuts. Therefore employment change over the next decade could be significantly different, with lower or negative growth in financial and public services, and very likely lower growth overall. This change does not necessarily mean that the overall post-industrial trend of manufacturing decline and knowledge economy expansion will be altered.

5.2.2   Spatial Structure of Employment in Greater London and the South East

We now move from a sectoral analysis to exploring the geography of economic activities in the London region. The spatial distribution of total employment

provides a basic indicator of economic activity. The density of employment in Greater London is mapped at ward level[1] in Figure 5.12 using 2001 census data.
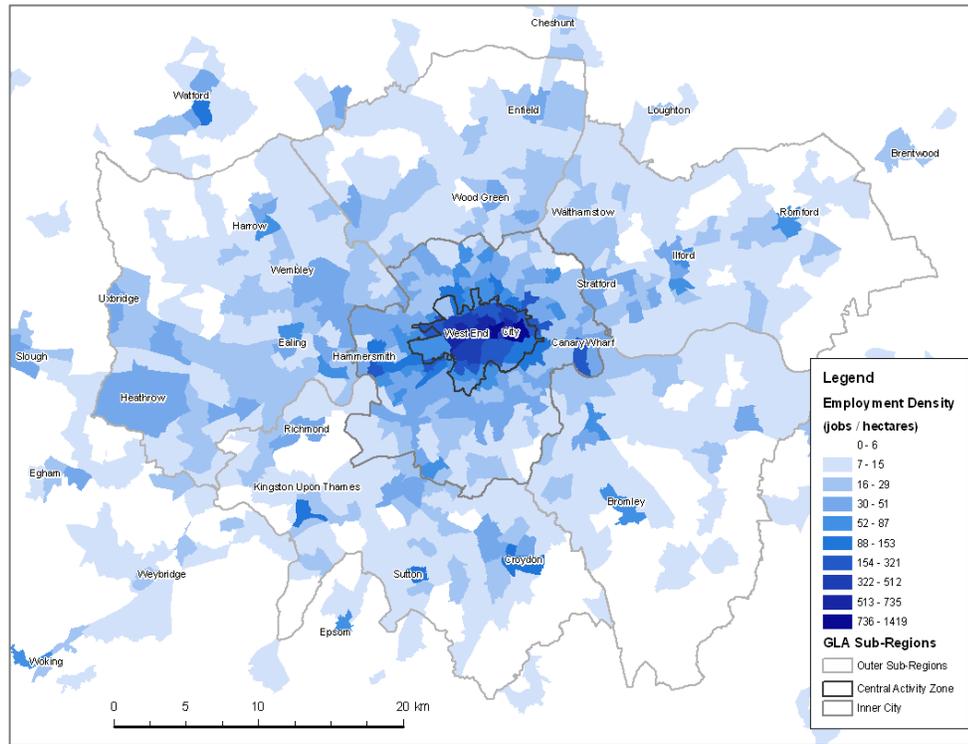
Figure 5.12: Greater London Employment Density and Sub-Regions from 2004 London Plan. Data Sources: Census 2001 (ONS, 2010b); Greater London Authority (2004).

A high degree of employment centralisation is clearly apparent, with wards in the City and West End exceeding 1000 jobs per hectare. The London Plan defined the Central Activities Zone (CAZ) in respect of the central area's global business, government, culture and tourism roles. The sub-region boundaries from the 2004 London Plan are also included. The Inner City contains moderately high employment densities, particularly at the sub-centres of Canary

---

[1] Note that there are some problems with using ward level geography for employment analysis. Wards were developed to provide approximately even numbers of residents in each zone, and so employment areas which lack residents are grouped with adjacent residential areas, affecting density measures. A solution to this issue is to use real-estate data, as discussed in Section 5.3.

Wharf and Hammersmith. Employment totals by sub-region are provided in
Table 5.5. This strongly emphasises the centralisation trend, with 52% of jobs in
the CAZ and Inner City.

Table 5.5: Employment by Greater London Sub-Region 2001.
Data Source: Census 2001 (ONS, 2010b).

Greater London Sub-Region	Employed and self-employed	
	Total	**%**
City Centre (CAZ)	1,247,542	32.04
Inner-City (ex. CAZ)	778,799	20.00
North	264,711	6.80
North-East	333,035	8.55
South-East	306,594	7.87
South-West	402,375	10.33
West	561,151	14.41
Greater London Total	3,894,207	100

Beyond the Inner City towards Outer London, employment densities are much
lower with small clusters of higher densities in town centres. The largest of the
Outer London centres is Croydon. The biggest employment concentration in
Outer London is not however found at a traditional town centre, but is rather at
Heathrow airport, which has 69,000 jobs in the 2001 census and has expanded
significantly in subsequent years. The presence of Heathrow alongside the
Western Corridor means that the West sub-region has the largest employment
total of the outer sub-regions. London's west-east division is a theme we will
return to in the discussion of employment specialisation in 5.2.4 and 5.2.5.

Extending the employment density mapping to the wider South East region, we
can see in Figure 5.13 that London strongly dominates the region, and that it is
surrounded by a cluster of many small employment centres within the Outer
Metropolitan Area. Larger towns and cities, such as Southampton, Norwich and
Milton Keynes, are located beyond the immediate radius of Greater London. The
employment totals are shown in Table 5.6, with Greater London comprising 39%
of the jobs in the Greater South East. The high percentage of GSE employment
found in the Outer Metropolitan Area (27%) emphasises the concentration of

South East employment in a relatively close distance (i.e. within 50 km) of
Greater London.
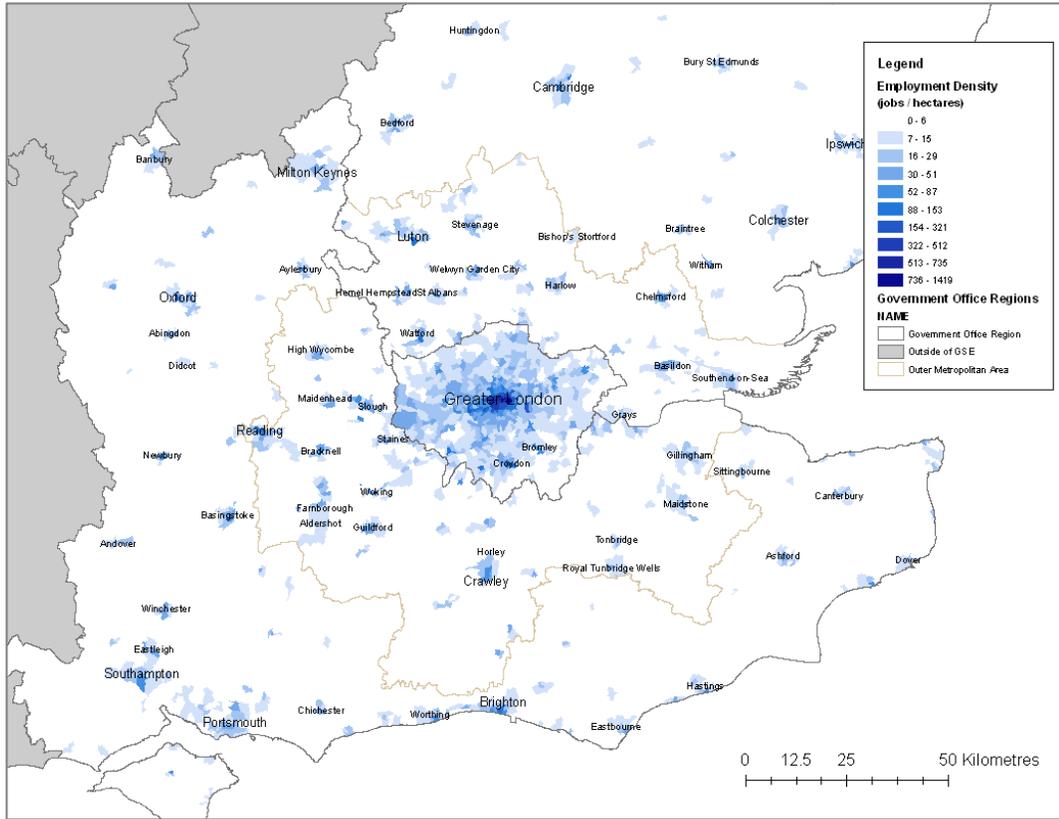
Figure 5.13: South East Employment Density and Sub-Regions.
Data Source: Census 2001 (ONS, 2010b).

Table 5.6: Employment by Greater South East Sub-Region 2001.
Data Source: Census 2001 (ONS, 2010b).

Greater South East Sub-Region	Employed and self-employed	
	Total	**% of GSE**
Greater London	3,894,207	38.61
East of England GOR	2,431,533	24.11
South East GOR	3,760,446	37.28
Greater South East Total	10,086,186	100

Outer Metropolitan Area (not including Greater London)	2,736,826	27.13

207

In summary, the aggregate spatial structure of employment in London shows a high degree of centralisation, both at a city scale, where Central London dominates Greater London, and at a regional scale, where Greater London dominates the wider South East region. In aggregate employment terms, this pattern supports an overall monocentric interpretation of London's employment geography, although there are significant employment totals beyond Greater London, particularly in the 50km radius of the Outer Metropolitan Area.

5.2.3   The Geography of Employment Change in the London Region

The spatial analysis of change in employment can be used to identify which areas are expanding and declining and how the geography of business activities is shifting over time. In this sub-section, aggregate employment totals for all sectors are mapped. Two data sources are used to analyse employment change: census journey to work data to measure employment change between 1991 and 2001, and the Annual Business Index (ABI) to explore changes between 1998 and 2004. Neither of these data sources are ideal and several issues limit the accuracy of measuring the geography of employment dynamics. The 1991 census journey-to-work data is only a 10% sample compared to the 100% sample in the 2001 data. The ABI is also a 10% sample and its format was changed in 2006. Subsequently mapping analysis of employment change is somewhat error prone and a degree of caution should be taken in the interpretation of the results.

The change in total employment between 1991 and 2001 according to census journey-to-work data is mapped at ward level in Figure 5.14. The patchwork of job gains and losses in close proximity is indicative of noise resulting from the 1991 sample size. Despite this limitation, there is an overall pattern with the most dramatic growth in Central London, Canary Wharf and Heathrow. These trends match the expansion of financial and business services, tourism and airport activities discussed in Sub-Section 5.2.1. The figures at sub-region level shown in Table 5.7 indicate that 52% of Greater London's growth occurred within the Inner City and CAZ. Growth in the Outer London sub-regions is much smaller in absolute terms, with only the West sub-region exceeding 100,000 new jobs. The Outer London sub-regions are however broadly comparable in terms of percentage growth. Paradoxically this centralisation trend occurs in tandem with

decentralised growth, as the Outer Metropolitan Area has a higher percentage growth than Greater London, and the total employment expansion is of similar magnitude to the Greater London total. Figure 5.14 shows this growth to be distributed throughout OMA towns, with a particular concentration in the 'Western Sector' around Reading, Bracknell and Farnborough.
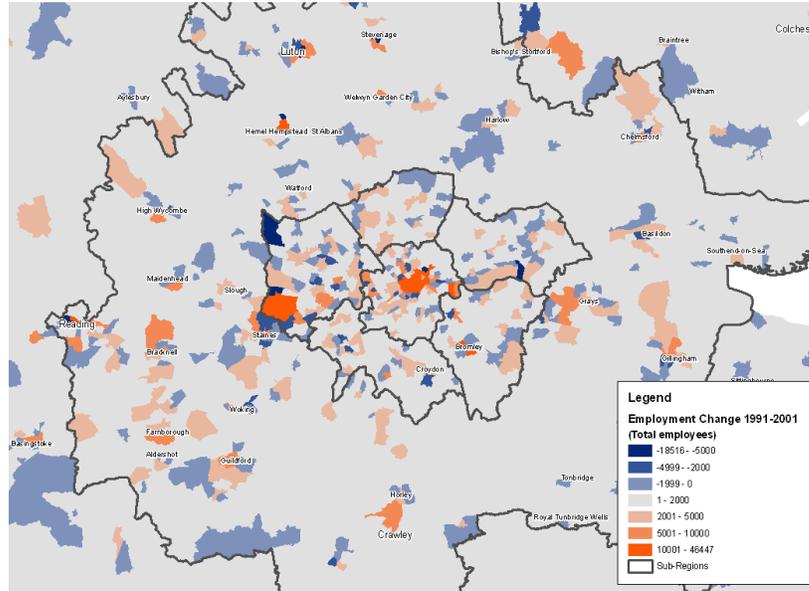
Figure 5.14: Total Ward Level Employment Change 1991-2001.
Data Sources: Census 1991, Census 2001 (ONS, 2010b).

Table 5.7: Employment Change by Sub-Region 1991-2001.
Data Sources: Census 1991, Census 2001 (ONS, 2010b).

Sub-Region	Employment Totals		Employment Change		
	1991	2001	Total	%	% of Gr. Ldn.
Inner London	1,580,600	1,993,131	412,531	26.10	52.39
North London	203,480	262,936	59,456	29.22	7.55
North-East London	267,960	328,488	60,528	22.59	7.69
South-East London	228,510	301,762	73,252	32.06	9.30
South-West London	322,560	400,422	77,862	24.14	9.89
West London	454,510	558,261	103,751	22.83	13.18
Greater London Total	3,057,620	3,845,000	787,380	25.75	100.00
Outer Metropolitan Area	2,026,220	2,717,258	691,038	34.10	87.76

For the analysis of more recent employment change the Annual Business Index (ABI) was used. The format of the ABI changed significantly in 2006 which

209

creates problems for spatially disaggregate time-series analysis. We therefore focus on the period 1998-2005. Note that to improve the sample size the employment values for individual years are the average of three consecutive years (e.g. 1999 is the average of 1998-2000) to boost the sample size. Employment change between 1999 and 2004 is mapped at district level in Figure 5.15. This period covers a recession in the years 2000-2001, leading to job losses in many sectors, including high value financial industries and particularly IT companies connected to the 'dot-com crash' in early 2000. Furthermore manufacturing continues to be in decline in this period, shedding 73,000 jobs in Greater London, and a similar number in the Outer Metropolitan Area (Table 5.8). Subsequently the analysis describes a period of relatively weak economic growth, and in many areas employment losses.
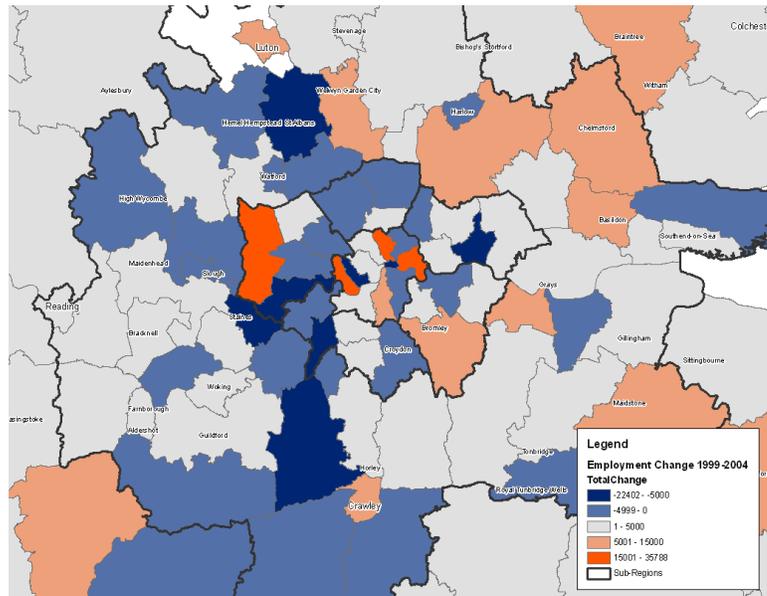
Figure 5.15: Total Employment Change District/ Unitary Authority 1998-2004. Data Source: Annual Business Index 1998-2004 (ONS, 2010c).

The general pattern of growth is similar to the census analysis, with the Inner City and Heathrow being the main growth poles. In fact the centralisation pattern is exacerbated in this period, with Outer London showing a net jobs loss. Areas of jobs losses also include the most economically dynamic regions, such as the City of London, likely affected by restructuring in financial services, and much of the Western Sector which, as a major cluster of UK information technology industries, is particularly exposed to technology focussed recessions

210

(discussed further in Sub-Section 5.2.5). Despite stagnation in the West, other areas of the Outer Metropolitan Area perform relatively well (particularly airports, and areas to the north-east) and it again considerably outperforms Greater London's percentage growth rate.

Table 5.8: Employment Change by Sub-Region 1998-2004
Data Source: Annual Business Index 1997-1999, 2003-2005 (Nomis, 2010).

Sub-Region	All Employment Totals		Employment Change				
	1999	2004	Total	%	% Gr. Ldn.	Services	Manufac.
Inner London	2,064,228	2,126,047	61,819	2.99	104.75	86,942	-19,917
North	268,461	265,539	-2,922	-1.09	-4.95	8,737	-7,389
North-East	322,057	275,607	-2,741	-0.85	-4.64	12,951	-15,119
South-East	289,234	297,544	8,310	2.87	14.08	17,092	-6,698
South-West	410,048	400,085	-9,961	-2.43	-16.88	1,314	-10,547
West	573,151	577,662	4,511	0.79	7.64	22,639	-14,133
Greater London Total	3,927,179	3,986,193	59,016	1.50	100.00	149,675	-73,803
Outer Metropolitan Area	2,601,258	2,659,909	58,656	2.25	99.39	123,396	-72,935

In summary, there are two main trends in employment dynamics in the London region that are simultaneously reinforcing and counteracting the traditional monocentric structure. Firstly recent employment growth in Greater London has been highly centralised, with over 50% of new jobs between 1991 and 2001 within the Inner City. Outside of the growth pole of Heathrow Airport, Outer London has seen lower growth and appears to have experienced jobs losses in the early 2000's, affected by manufacturing decline and services restructuring. Paradoxically this Greater London centralisation trend is matched with decentralisation in the wider region, with the strongest growth rates outside of the GLA boundary in the Outer Metropolitan Area. Thus in addition to centralisation, there are polycentric trends at a regional scale.

5.2.4   Employment Specialisation by Occupational Class

We now move on from aggregate employment analysis, to considering what type of economic activities occur in different employment centres. Employment specialisation relates to the value and productivity of particular industries and jobs. We consider occupational class disaggregation, where employment is

classified by skill level in this sub-section, and sectoral disaggregation, where employment is broken down by industrial classifications in the next sub-section. Occupational class analysis provides a broad overview of specialisation with the advantage that functional separation within sectors is included, as for example distinguishing between front and back offices in services, or between production and R&D activities in manufacturing. Researchers have argued that functional specialisation is increasing due to knowledge economy agglomeration trends and the increased benefits for large multinationals (Duranton and Puga, 2001).

Data on occupational class can be derived from the UK 2001 census. This includes a nine category classification of jobs types, from Managerial to Elementary employment. An example of the data is shown in Figure 5.16, comparing the occupational class profile of wards in the City of London and Croydon. The City is dominated by the top four classes, in particular managerial and professional jobs, whilst the lower five occupational classes are almost entirely absent. Meanwhile Croydon has a lower proportion of the managerial and professional categories, whilst having a significantly larger proportion of administration and sales/customer service jobs. This is clearly indicative of a back-office role for Croydon.
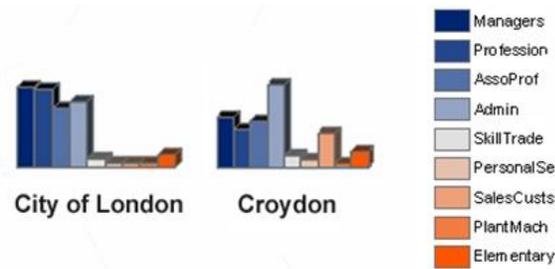
Figure 5.16: Workplace Occupational Class Data for City of London and Croydon Town Centre. Data Source: Census 2001 (ONS, 2010b), ward scale.

The 2001 census data can be used to map the occupational classification across Greater London and the Outer Metropolitan Area. There are a number of methods by which the occupational class data can be summarised. Previous studies have used the measure of proportion of managerial jobs to indicate specialisation (Duranton and Puga, 2001) and this approach is followed here in Figure 5.17. The most immediate pattern is the stark east-west division in

employment specialisation. High proportions of management employment are restricted to Central London, Canary Wharf, the Western Corridor and Western Metropolitan Centres. Whilst Heathrow is low specialisation by this measure (due to the dominance of customer service and manual jobs), nearby business parks are of high specialisation at a level comparable to Central London. Meanwhile low specialisation jobs dominate North, East and South London. A subtly different picture emerges if we use the top three professional occupational classes for our specialisation indicator as shown in Figure 5.18.
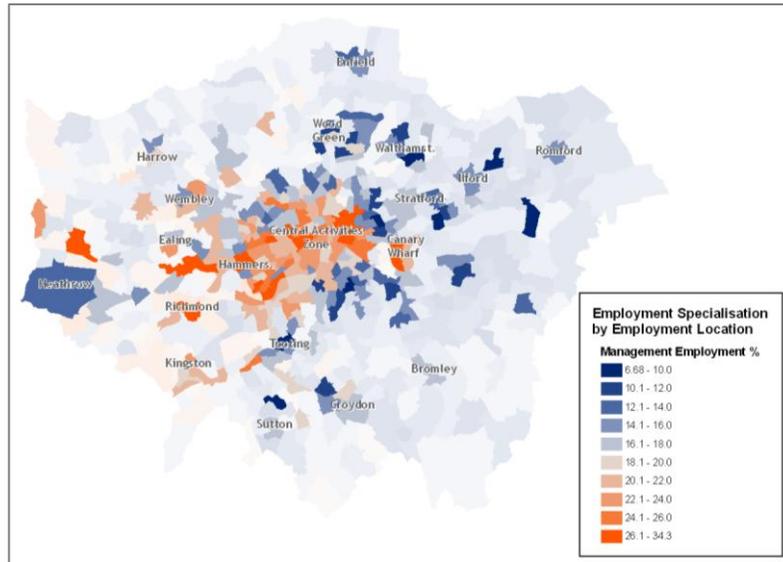
Figure 5.17: Occupational Class Indicator, Managerial Employment, for Greater London. Data Source: Census 2001 (ONS, 2010b).
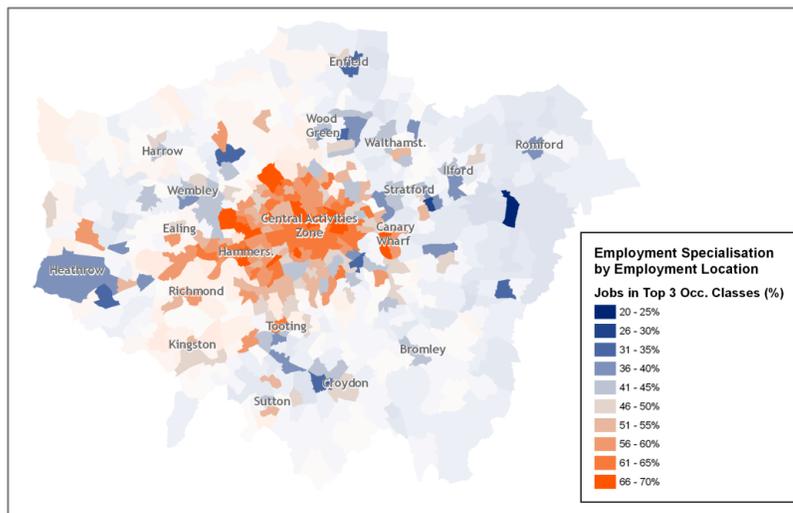
Figure 5.18: Occupational Class Indicator, Managerial, Professional and Associate Professional Employment, for Greater London. Data Source: Census 2001 (ONS, 2010b).

213

In the Figure 5.18 indicator the Inner City is more strongly highlighted, due to the prevalence of professional sectors such as health and education. The majority of Outer London remains low specialisation. Note that a density threshold has been applied to Figures 5.17 - 5.19 so that high employment density wards are highlighted.

When the specialisation analysis is expanded to the wider region it is clear that the east-west division continues westwards. The Western Corridor of high specialisation jobs extends into the Western Sector, with a number of centres such as Bracknell and Maidenhead including levels of managerial employment comparable to Central London. Low specialisation jobs dominate towns to the east, as well as larger more distant towns to the north and south, including the airport locations of Crawley and Luton.
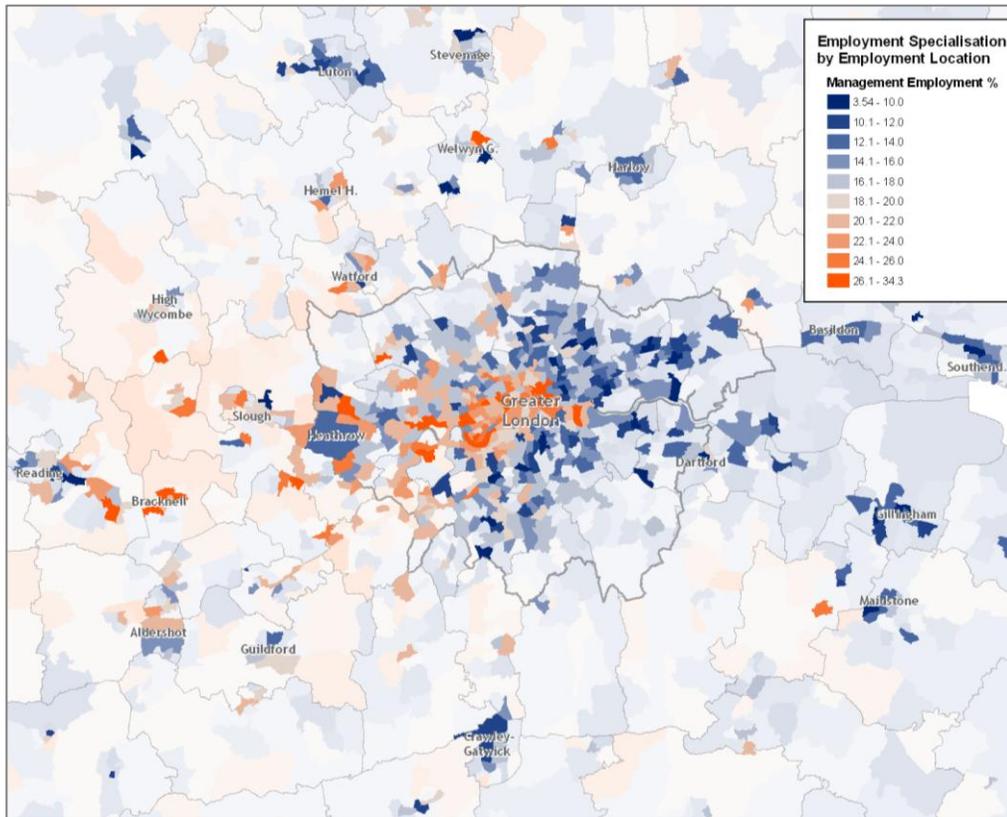
Figure 5.19: Occupational Class Indicator, Managerial Employment, for London Outer Metropolitan Area. Data Source: Census 2001 (ONS, 2010b).

Overall, there is a strong pattern of spatially uneven sub-regional employment specialisation in the study area. Within the GLA, Central London and the Western Corridor display much higher proportions of high value occupational classes, while East London and much of Outer London are of low specialisation. This pattern extends to the Outer Metropolitan Region, with high specialisation in the Western Sector. These trends are indicative of strong agglomeration processes in firm location patterns, and the continuation of historical divisions between East and West London.

5.2.5   The Geography of Sectoral Specialisation

The employment specialisation analysis continues in this sub-section with the detailed spatial analysis of business sector concentrations in London and the Outer Metropolitan Area. The geography of business sectors is a fundamental aspect of agglomeration economies, and furthermore can be used to highlight the specialisation trends and business relationships within city-regions. The ABI data is again the basis of the analysis. Data from the years 1998-2002 have been averaged to enable comparability with the previous 2001 census analysis. A high level of sectoral detail has been used for this analysis to identify narrow specialisations. This increases the volume of results and to minimise this problem, low-concentration manufacturing sectors have been excluded as well as lower value wholesale, retail and non-air transport sectors. The sectors included are summarised at 2 digit level in Table 5.9. To simplify interpretation of the data, a colour code is used throughout this sub-section, grouping service classes into seven general categories, as shown in Table 5.9. Note that a small number of classes are ambiguous and relate to several categories. Defence and Higher Education are two such classes and have been included in the Public Service category, though are also related to the Research category.

Table 5.9: Overview of Sector Groups Included in the Sectoral Specialisation Analysis.

2 digit SIC 2003	Industrial Sector Group
22	Publishing, printing and media
55	Hotels and restaurants
62	Air transport
64	Post and telecommunications
65	Financial intermediation
66	Insurance and pension funding
67	Activities auxiliary to financial intermediation
70	Real-estate activities
72	Computer and related activities
73	Research and development
74	Other business activities
75	Public administration and defence
80	Education
85	Health and social work
92	Recreation, cultural and sporting activities
93	Other service activities

Financial Services
Business Services
Creative and Media Industries
IT, Research
Tourism, Heritage
Government, Public Services
Other

The analysis begins by looking at the spatial distribution of individual sectors, and we then move on to considering sectoral specialisation in particular employment centres. The most spatially clustered 4 digit sectors are shown in Table 5.10, measured using the Gedis-Ord G statistic (see Sub-Section 4.6.3). The results are normalised against the clustering of total employment; thus a result of 2 equates to clustering twice as high as aggregate employment. There is a very clear pattern to the results with financial services displaying by far the highest degree of spatial clustering, followed by media industries. Business services and IT/Research are more varied between sub-sectors. Finance, media and business services were the sectors identified earlier (sub-section 5.2.1) as London's most intense specialisations. Thus spatial clustering is most prevalent in these specialised knowledge-economy sectors. The Government and Public Sector classes are absent from Table 5.10 (except for Defence), indicating relatively low spatial clustering for these categories.

In Chapter 4 we identified monocentricity as the combination of clustering and centralisation, and polycentricity as the combination of clustering and decentralisation. In combination with the clustering statistic, a general measure of centralisation is provided in Table 5.10 with the distribution of employment broken down in percentage terms by sub-region, to test whether the most clustered industries are linked to more monocentric or polycentric forms. As can

be seen many of the most clustered sectors are highly centralised, exceeding 50% of jobs in the Central Activities Zone, particularly in finance and business services. There are several exceptions however of specialised industries which display clustering beyond Central London, including IT, Defence and several media sectors. Their geography of these more decentralised specialisations is explored in the next analysis.

Table 5.10: Sectors Showing Highest Degree of Spatial Clustering.
Data Source: Annual Business Index 1998-2002 (ONS, 2010c).

SIC	SIC Name	Clustering Getis-Ord G*	Z-Score	Sub-region Distribution %			
				Central	Inner	Outer	OMA
6720	Insurance Auxiliary	10.84	19.40	50.3	3	15	31.7
6712	Broking Fund Mng.	9.39	27.33	76.7	13.5	1.9	7.9
6511	Central Banking	9.29	6.75	95.2	0	0	4.8
6601	Life Insurance	9.25	20.47	31.6	0.5	10.8	57.1
6603	Non-Life Insurance	8.60	19.34	40.7	1.3	21.6	36.4
7411	Legal Activities	8.02	32.37	64.3	7.0	11.9	16.8
6523	Other Financial Inter.	7.79	24.71	54.6	35.2	3.5	6.7
6711	Finance Market Admin.	7.76	9.52	65.5	5.9	10.7	17.9
6512	Banks Building Soc.	7.28	28.62	51.9	12.7	15.1	20.2
2221	News Printing	4.34	7.02	2.4	59.4	3.2	34.9
6713	Financial Inter. Auxil.	4.13	17.98	42.0	23.4	10.9	23.7
2232	Video Reproduction	3.52	14.61	9.7	2.6	66.5	21.2
9220	Radio & Tel Activ.	3.00	16.23	39.9	33.3	19.7	7.2
9212	Motion-Pict. Video Dist.	2.71	6.92	48.1	34.0	11.1	6.8
7440	Advertising	2.51	29.44	51.2	10.0	15.5	23.2
6420	Telecommunications	2.48	18.32	33.5	5.5	18.5	42.5
9240	News Agency Activities	2.46	6.95	71.8	19.3	4.8	4.0
5510	Hotels	2.40	26.20	45.0	8.5	14.9	31.6
7240	Database Activities	2.34	11.06	43.3	4.3	16.7	35.7
9211	Motion-Pict Video Prod.	2.20	18.89	54.7	14.6	15.1	15.5
7412	Accountancy	2.14	11.83	51.2	5.0	15.9	27.9
7414	Business Mng. Consult.	2.07	33.68	38.8	10.1	16.5	34.6
6521	Financial Leasing	2.06	12.06	21.6	4.8	14.1	59.5
7522	Defence Activities	2.05	5.72	44.6	0.7	12.9	41.8
7012	Own RealEst. Buy & Sel.	2.04	25.44	42.9	10.9	23.8	22.4
	Total Employment	1	-	18.8	11.7	28.2	41.3

*Normalised against total aggregate employment; linear inverse distance function, threshold 2km.

We now move on to the business centre based analysis of sectoral specialisation. Before this analysis can be undertaken, the geography of business centres must be defined. Methods to achieve this have been discussed

previously in Section 4.6.3, involving density and total employment thresholds. Sub-regional thresholds were applied to cater to the distinct density contexts of Inner London, Outer London and the wider region[1]. The second issue to consider was that the basic threshold approach created a single combined centre for all of Central London. A defining characteristic of Central London is the presence of employment specialisation at local scales (Greater London Authority, 2004;2007b). Based on the Central London analysis from the London Plan and Office Policy Review, the Central London cluster was divided into seven sub-centres shown in Figure 5.20.

To simplify the extensive data for fifty-two employment centres, we concentrate on the strongest sub-regional employment concentrations, identified in the earlier employment density and specialisation analyses. These are Central London, West London and the Western OMA commonly referred to as the Western Sector (the full data on all centres is provided in Appendix B). Secondly the sector specialisation results for each employment centre are summarised with a minimum location quotient of 3 applied, as illustrated diagrammatically in Figure 5.21. There is an issue regarding the varying size of the employment centres, as quotients for large centres represent larger absolute numbers of employees than the same quotients in smaller centres. Total

---

[1] The more peripheral centres could be considered less important due to their lower density and total employment levels, and subsequently be removed from the analysis. Yet there are a far greater number of peripheral centres compared to Inner City centres and thus the combined employment levels are significant. Furthermore, as discussed earlier, important employment trends are occurring in Outer London and the wider region. Therefore a three level employment classification was used to capture the range of centres, with ward level density thresholds of 80 jobs/hectare in Inner London, 35 jobs/hectare in Outer London and 15 jobs/hectare in the OMA. The minimum centre size is 15,000 jobs (calculated using 2001 census data) although the majority of centres are considerably larger than this total. Finally the important centres of Heathrow and the Western Corridor were too low density to meet the threshold using the ward level geography. These are significant employment centres and were added manually to the business centre definition.

employment size figures for each of the centres are included in the diagrams to allow this issue to be considered.
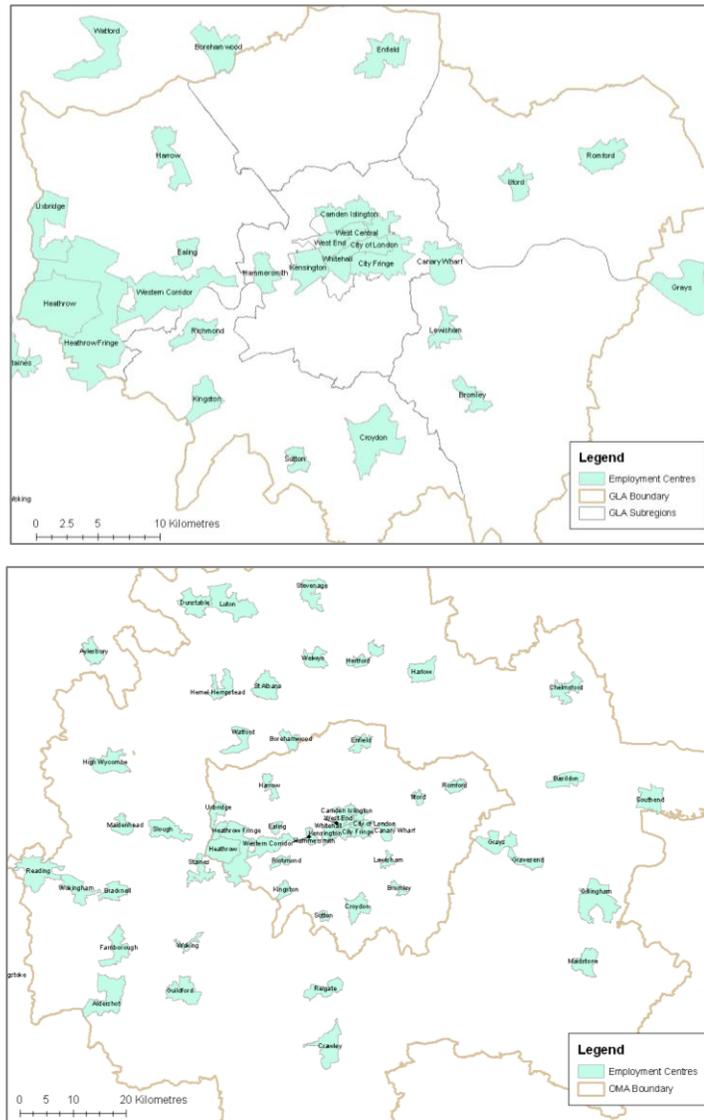
Figure 5.20: Employment Centre Analysis Results for Greater London and the Wider Region.
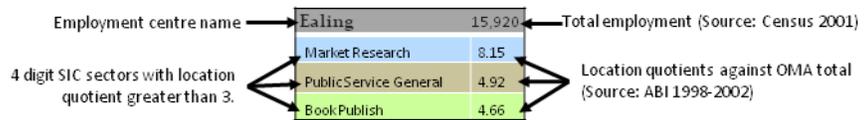
Figure 5.21: Employment Centre Specialisation Profile Example.

219

We begin the sector specialisation analysis with Central London, as shown in Figure 5.22. This features London's most prominent business centres, with the City, City Fringe and Whitehall each totalling hundreds of thousands of jobs. A high degree of sub-centre specialisation is clearly apparent with distinct functional roles for each centre, particularly in relation to the most definitive specialisations of central government functions in Whitehall and financial services in the City.
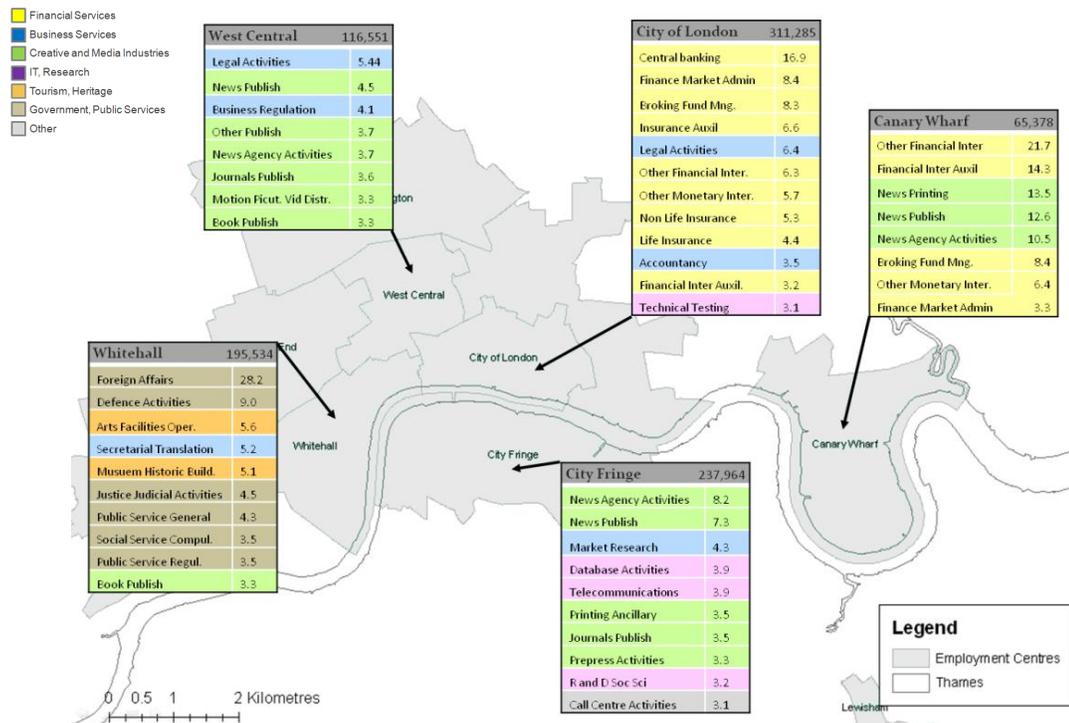
Figure 5.22: Central London Employment Centre Specialisations.
Data Source: ABI 1998-2002 (ONS, 2010c).

Looking in more detail there are some interesting comparisons. Since its inception, Canary Wharf has been regarded by the City of London as a threat in terms of attracting businesses away from the City to new and cheaper premises (Greater London Authority, 2007b). This can be interpreted in Figure 5.22 in terms of the shared financial and monetary intermediation (i.e. banking) sectors that both centres compete for. Yet on the other hand the competition appears to be resulting in complementary specialisation in different roles, with the City retaining insurance and business service roles, while Canary Wharf specialises in news media. Newspaper functions famously abandoned their tradition Fleet

Street location in the 1980's and 1990's for larger cheaper premises at Canary Wharf and the City Fringe. The City Fringe is also notable for not sharing a single sector with the City above the concentration threshold. The City Fringe attracts businesses which require close access to City clients but do not necessarily require the prestige and extra cost of locating within the City. Moving on to West London, we can see in Figure 5.23 a contrasting functional role dominated by creative and media sectors. Additionally there is tourism industry element around Kensington and the West End. The West End is of similar scale to the City and Whitehall, and includes the Soho cluster specialising in film, television and advertising roles (Nachum and Keeble, 2003). This appears to be part of a wider 'creative corridor' of similar industries particularly in Hammersmith (including BBC Television Centre, although this is currently relocating) and the Western Corridor (including Sky Television). These television centres are anchor points for co-located industries, such as the Video Reproduction and Sound Publishing sectors highlighted in Figure 5.19, creating a distinct sub-regional functional cluster.
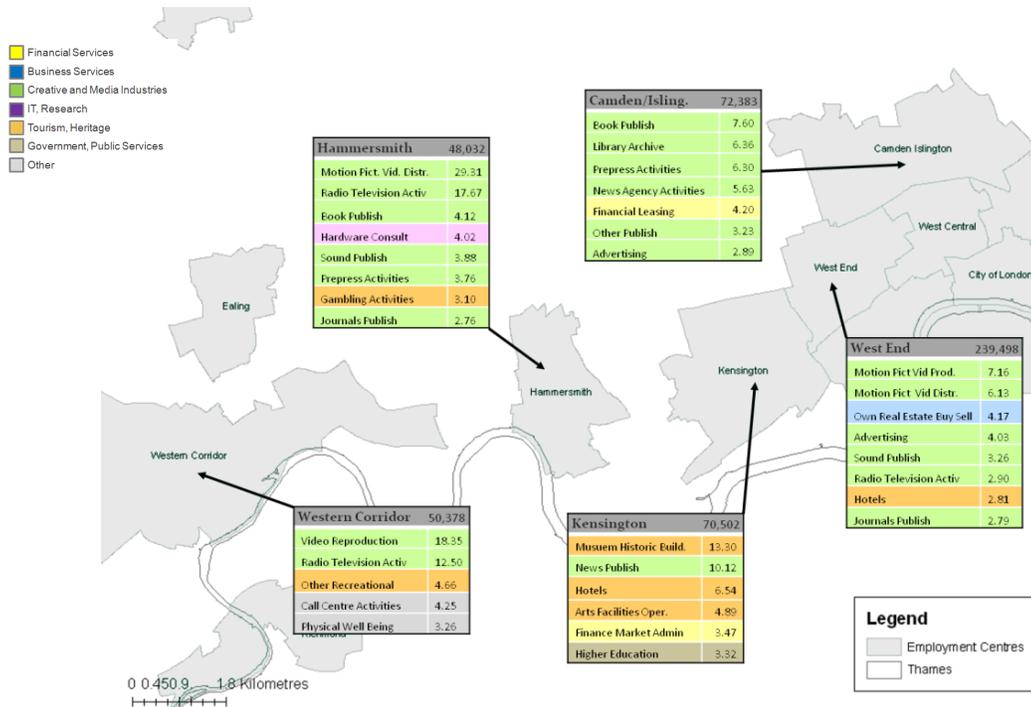
Figure 5.23: West London Employment Centre Specialisations.
Data Source: ABI 1998-2002 (ONS, 2010c).

The trend of sub-regional clustering is also spectacularly apparent in the Western Sector. IT industries, which are relatively weakly concentrated within Greater London, dominate the network of towns in the Western Sector as shown in Figure 5.24. A wide range of software, hardware and research functions are present, including some very high location quotients. A more modest presence of financial and business services can also be identified. Note that the centres are much smaller in size than Greater London centres, with Reading being the largest. The pattern of Information Technology specialisation in the Western Sector is largely a sign of economic success and dynamism. It does however lead to risks of over-specialisation and subsequent exposure to international market downturns. Decline in IT sectors over the last ten years (Sub-Section 5.2.1) explains weaker economic growth in the Western Sector in the early 2000's (Sub-Section 5.2.3).
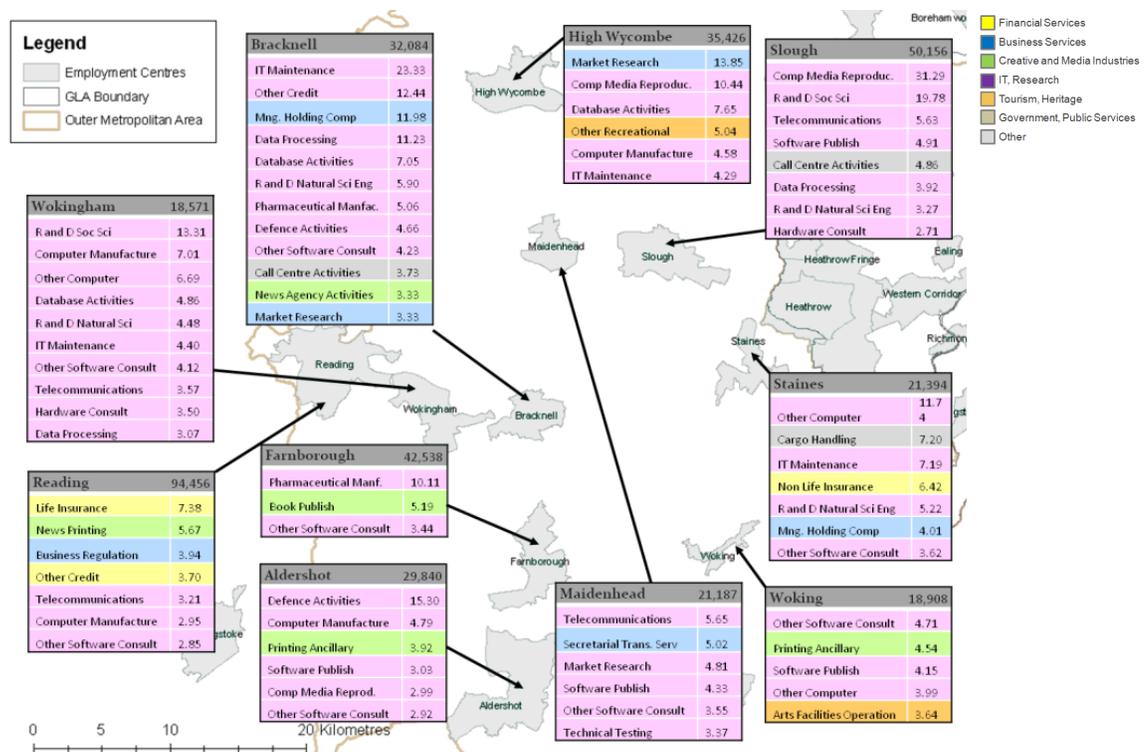
Figure 5.24: Western Sector Employment Centre Specialisations.
Data Source: ABI 1998-2002 (ONS, 2010c).

Finally it is useful to compare these areas of high specialisation to the Outer London centres, which are both lower specialisation and have displayed recent employment losses. Sector specialisations for the major Outer London centres

are shown in Figure 5.25. The dominance of government and public service functions in these centres is clearly apparent. Some business service specialisations are present, as are publishing functions for those centres on the fringe of the Western Corridor. Additionally some financial service concentrations can be seen, particularly insurance, likely in a back-office capacity. Insurance was identified as displaying recent decline in the 5.2.1 sectoral overview. Note that retail sectors have been excluded from this analysis, and these are a central part of the economy of many Outer London centres, as discussed further in Section 5.3 real-estate analysis.
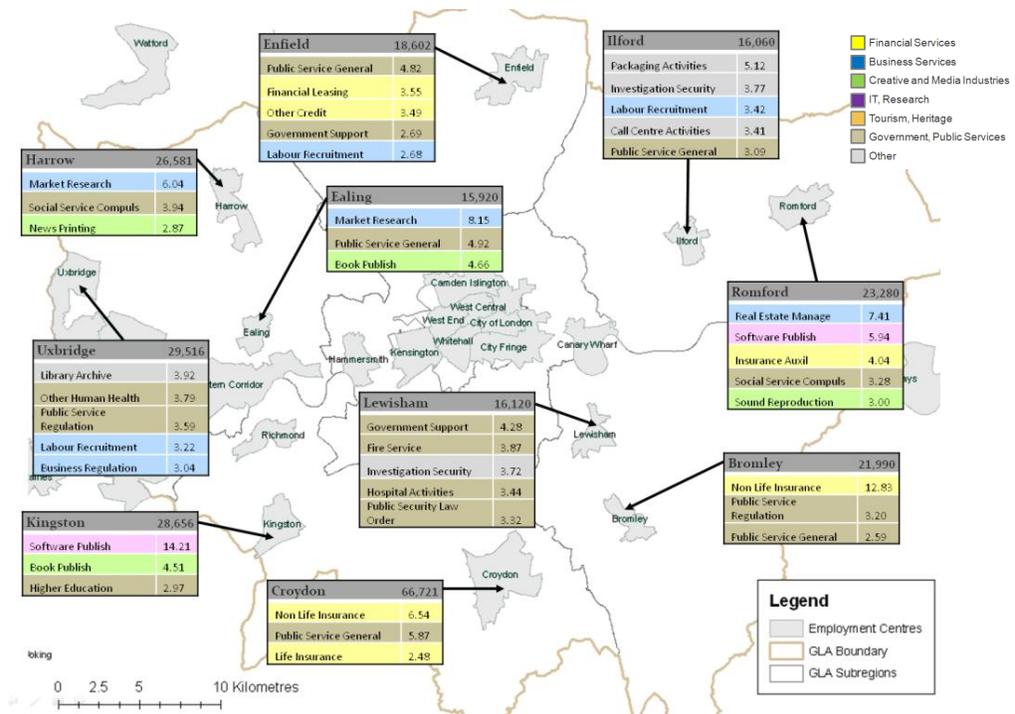
Figure 5.25: Outer London Employment Centre Specialisations.
Data Source: ABI 1998-2002 (ONS, 2010c).

Overall, London displays a high degree of employment sector specialisation at the scale of local employment centres, with some spectacularly high concentrations. In several cases employment centres are linked together into sub-regional networks of complementary functions, particularly in Central London for financial and business services and news publishing; West London for creative and media industries; and the Western Sector for IT. Both the sectoral and occupational class analyses strongly highlighted these sub-regions. The highly specialised activities occurring in the wider region supports the

223

polycentric assessment of the London regions economic geography. Beyond these specialised centres, economic stagnation in Outer London centres is connected to the prevalence of public service activities, and to back-office financial services which have been restructuring and cutting jobs.

5.2.6 Summary

This discussion of employment geography has provided overwhelming evidence of strong sub-regional spatial processes in employment and firm location in the London region that create highly localised intra-urban patterns in growth, decline and specialisation. There are simultaneous processes of centralised and decentralised growth occurring in the London region, neither supporting a straightforward monocentric or polycentric interpretation of urban form. The intra-metropolitan scale and employment survey focus of this analysis has been successful in identifying and quantifying these processes.

The dynamics of the post-industrial economy and strengthening of London's world city status has greatly favoured business service, financial and tourism growth which in turn has overwhelmingly benefitted Central and Inner London, as the core of the financial, business and media services. Over 50% of new Greater London jobs between 1991 and 2001 were located within Central and Inner London. Furthermore Outer London recorded lower growth in the 1990's and lost jobs in the early 2000's, accelerating these divergent patterns in growth. Outer London has been disproportionately affected by the continuing manufacturing decline and restructuring in service industries such as insurance, with cuts in back-office jobs. The Western Corridor is distinct from the general Outer London trend, benefitting from a sub-regional agglomeration of media industries and the continued growth of Heathrow. This evidence supports an overall monocentric interpretation of London's employment geography with Central and Inner London dominating Greater London. Paradoxically this centralisation trend is matched with decentralised growth beyond Greater London with growth rates outside of the GLA boundary exceeding Central London, and comparable absolute increases in OMA employment to the Greater London total. Thus at the regional level monocentric and polycentric trends in employment geography are occurring simultaneously. The prime example of

economic dynamism in the wider region is the Western Sector, with spectacular concentrations of IT industries. This sub-region expanded significantly in the 1990's, though stalled in the early 2000's IT related recession. These changes are evidence of more dispersed polycentric urban regional trends.

5.3 Real-Estate Analysis of Employment Activities in Greater London

This section builds on the previous economic geography of London, providing a complementary real-estate analysis of business functions and allowing relationships between economic structure and the physical built-environment to be explored. The extent to which development is directing growth are explored, and relationships between the property market indicator of rental costs and patterns of specialisation discussed in the previous section are tested. Real-estate data relates to three aspects of urban structure: density, in terms of how intensively the built-environment is developed; function, in terms of property use classifications; and finally property market value, in terms of rent. These aspects can be investigated simultaneously, and insights can be gleaned by the visual and statistical analysis of interrelationships between form, function and value.

The core data for this analysis is the UK Valuation Office Non-Domestic Rates database for 2005, which provides detailed information on all non-domestic properties in the UK. Only Greater London data for the year 2005 was available for this research, and so wider regional processes are not analysed. After data processing, classification and validation (detailed in Appendix D) this dataset can be used to create a fine-scale spatial database of the density and function of commercial property. Urban density is analysed in 5.3.1, followed by function and mix-of-uses in 5.3.2. The centralisation and clustering statistics are applied to the real-estate data in 5.3.3, and then the real-estate rental data is explored in 5.3.4. Finally as the dataset provides only information on 2005, an additional temporal analysis of planning completions data is provided in Sub-Section 5.3.5 to allow the analysis of urban development dynamics.

5.3.1   Built-Environment Density Analysis

Analysis and visualisation of the real-estate database allows the geography of intra-urban business centres to be mapped, and provides a complementary analysis to the employment geography from Section 5.2. We begin by summarising the sub-regional distribution of floorspace, as shown in Table 5.11. The distribution matches the highly centralised pattern identified in the employment geography analysis, particularly for office space with a massive 57% of office floorspace within the Central Activities Zone. Retail and Industrial floorspace is more evenly dispersed. In Outer London the West and South-West sub-region has the largest proportions of office floorspace.

Table 5.11: Floorspace by Greater London Sub-Region 2005. Data Source: VOA 2005.

Sub-Region	Functional Group							
	Office Floorspace		Retail Floorspace		Industrial Floorspace		All Floorspace	
	Total (000's m²)	%	Total (000's m²)	%	Total (000's m²)	%	Total (000's m²)	%
City Centre (CAZ)	14,057	57.0	2,003	16.9	903	4.3	16,963	29.5
Inner-City	4,667	18.9	2,655	22.4	3,358	16.0	10,680	18.6
North	653	2.6	1,100	9.3	2,438	11.6	4,190	7.3
North-East	710	2.9	1,584	13.4	3,398	16.2	5,693	9.9
South-East	710	2.9	1,344	11.4	2,790	13.3	4,843	8.4
South-West	1,636	6.6	1,596	13.5	2,236	10.7	5,467	9.5
West	2,232	9.1	1,551	13.1	5,866	27.9	9,650	16.8
% of Total	42.9		20.6		36.5		100	

The extreme dominance of Central London for office activities is clearly highlighted in the 3D mapping visualisation in Figure 5.26. The grid is extruded in proportion to total floorspace, and as all grid squares are of equal area (500 metres by 500 metres) this provides a detailed density measure. Note that a minimum floorspace threshold of 5000 m² has been applied to all the density maps to remove small-scale centres and improve visual clarity. Within the central agglomeration the highest office densities are found in the City of London. The central agglomeration is also surrounded by moderately high density office areas in the neighbouring inner-city. The very highest office

densities are located at Canary Wharf, the tertiary centre in inner-east London. Canary Wharf has expanded rapidly since its formation in the mid-1980's (as identified earlier in Section 5.2) and now includes a cluster of London's tallest buildings. In Outer London the office market is significantly weaker, with only a few modest centres such as Croydon. The area of Outer London with the strongest office market is to the west, which runs though the inner-city towards Heathrow Airport. Office activities here are relatively dispersed rather than clustered.
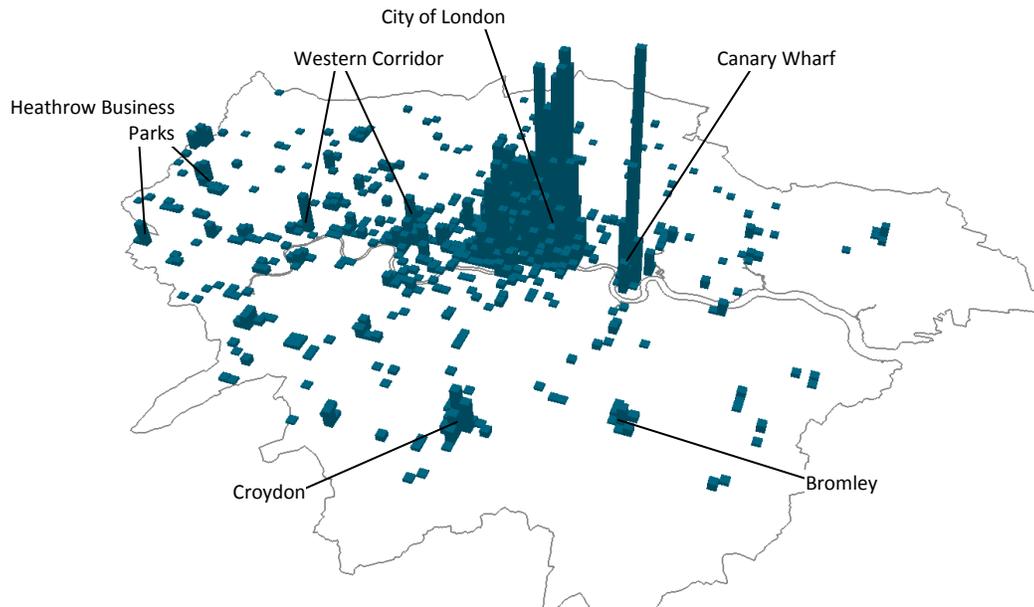
Figure 5.26: Floorspace Density for the Office Functional Group. Data Source: VOA 2005.

The retail floorspace density map in Figure 5.27 provides an interesting contrast to the office pattern. An identical extrusion function is applied to both the office and retail 3D maps to enable direct comparison. The city centre remains the largest agglomeration, this time concentrated in the West End. The relative dominance of the central retail cluster is considerably less compared to office activities, and there is a much stronger network of retail sub-centres in Outer London. There are major retail concentrations at Kingston and Croydon, and smaller local clusters following the network of town centres in Inner and Outer London. Unlike office space there is no western corridor bias, with retail centres attracted to all suburban areas. Overall the retail floorspace pattern fits much more closely to a balanced central-place hierarchy pattern (discussed in Chapter

2), reflecting the location of consumers with less extreme agglomeration than office activites.
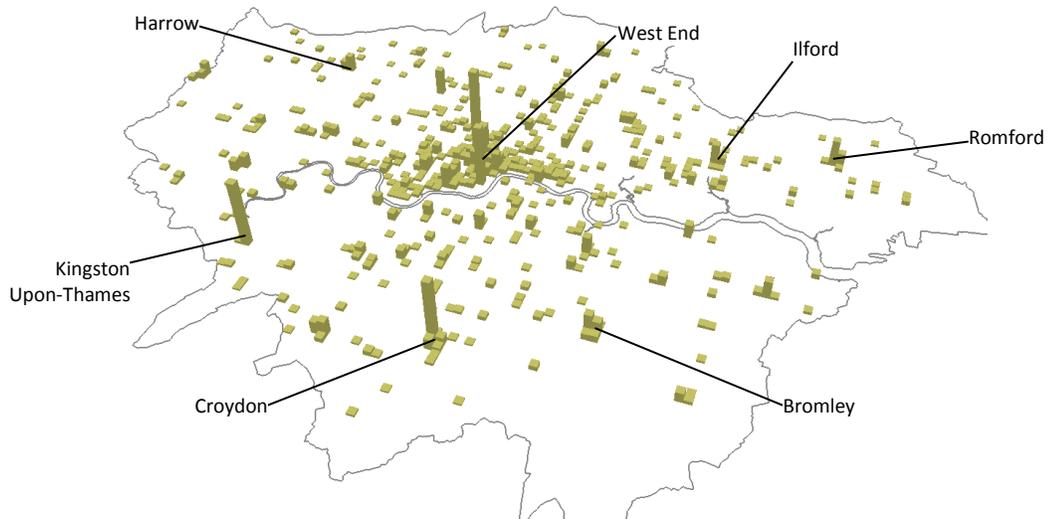
Figure 5.27: Floorspace Density for the Retail Functional Group. Data Source: VOA 2005.

The geographical pattern of industrial functions lacks the high density clusters of office and retail activities and consists of looser industrial corridors spread across large areas of the city, as shown in Figure 5.28. The two major corridors are the Lee Valley and along the Thames in East London, both of which are traditional manufacturing areas. Another area of longstanding industrial activity is in North-West London around Park Royal and Wembley. The growth of Heathrow has also attracted significant warehousing functions. A surprising volume of industrial warehouses and workshops are located in the inner-city, particularly south of the Thames. Industrial properties in these areas have been prime targets for office and residential conversions in the extensive gentrification processes that have transformed Inner-London over the last thirty years, but it appears that modest industrial property densities are still present in areas of the inner-city.
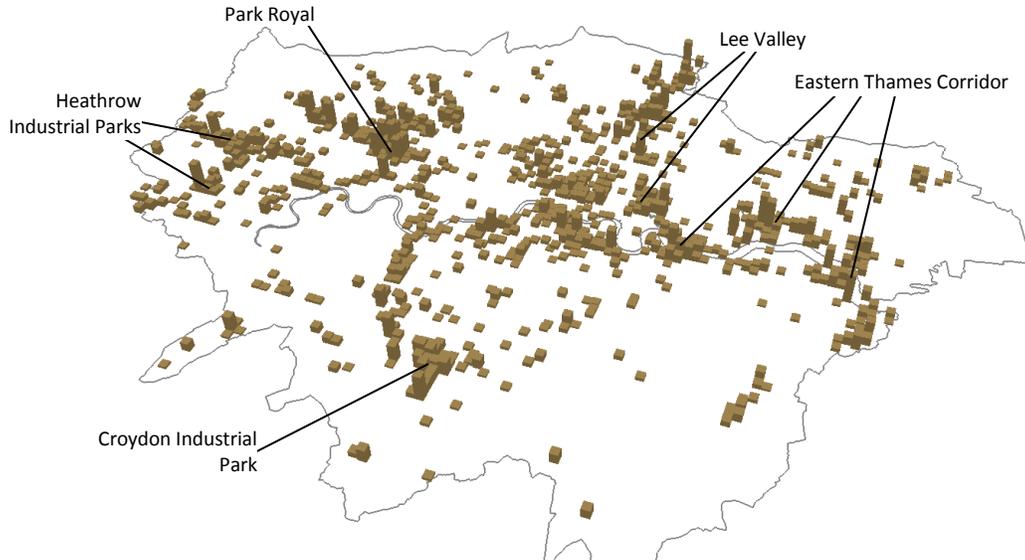
Figure 5.28: Floorspace Density for Industrial Functional Group. Data Source: VOA 2005.

5.3.2   Mix-of-Uses and Functional Diversity

It is possible to combine the real-estate function groups to explore mix-of-uses and diversity. The various employment centres in Greater London have particular profiles in terms of their mix-of-uses and density. This can be highlighted using mapping analysis and through diversity statistics. The 3D visualisation techniques used in the previous section can be expanded to include multiple functional groups, as illustrated in Figure 5.29. Office and retail functions are stacked on top of each other in the manner of a 3D bar graph.

Within the central agglomeration the shift between the office focussed City of London to the east and the more retail orientated West End can be clearly seen. In Outer London Metropolitan Centres such as Croydon, Romford and Uxbridge display mixed use activity, combining office and retail functions. This contrasts with dispersed mono-functional office developments that are evident in the business parks surrounding Heathrow and the Western Corridor. These patterns are likely to be indicative of car-orientated edge-city forms, as explored further in Chapter 6.
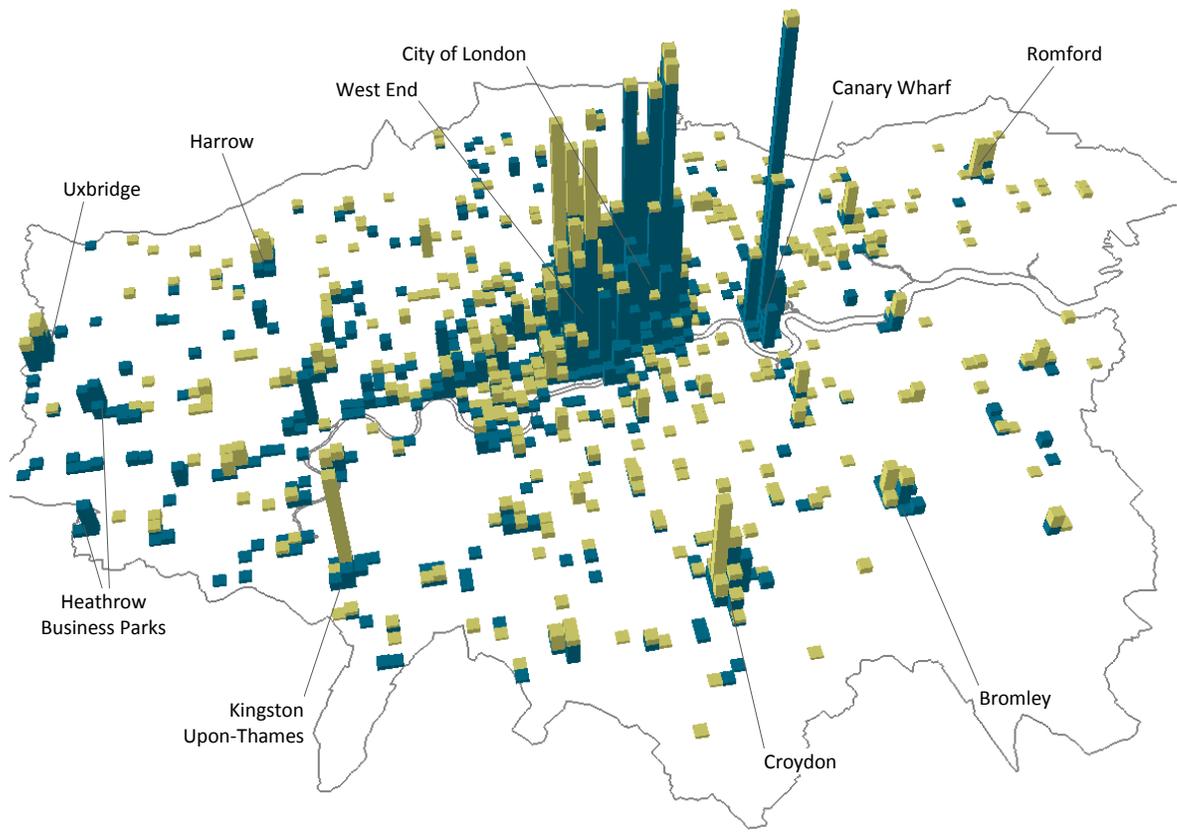
Figure 5.29: Office (blue) and Retail (yellow) Floorspace Density in Greater London.
Data Source: VOA 2005.

Functional diversity can also be analysed using statistical indices. For the calculation of these measures the functional super-groups in the classification have been used (see Appendix D) to avoid skewing the statistics towards groups with a greater number of sub-groups. As floorspace information is not available for Local and Public Services, the indices are calculated using the rateable value measure. The standard index of diversity (Sub-Section 4.6.2) sums the squares of the proportion of each group against the local total. It is in essence a measure of local functional balance. For example, a perfectly balanced grid square with rateable value divided equally between the five groups would measure 0.8, and a completely mono-functional grid square would score 0. As can be seen in Figure 5.30, using this measure the inner-city is the most functionally diverse and balanced area, and outer centres such as Croydon, Kingston and Ilford are also recorded with high functional diversity. Functionally imbalanced areas include the industrial corridors identified earlier in Section 5.2.6, the business

parks around Heathrow Airport, and finally the city centre, particularly the City of London. The reason why the City of London is measured as imbalanced is that office functions are so dominant (between 80-90% of all rateable value) that this dwarfs all other functions, despite there being a moderate presence of retail and local service functions in this area. We can use a density-diversity index (Sub-Section 4.6.2) to get a different perspective on diversity, this time summing the proportion of each functional group against the regional maximum. This is therefore a measure of the intensity of activity for all functions rather than relative local balance. This produces a contrasting picture, as can be seen in Figure 5.31, with the city centre containing the most intensive activity. Note it is the West End that scores most highly, as it includes a wider range of office, retail and restaurant/leisure activities compared to the City.
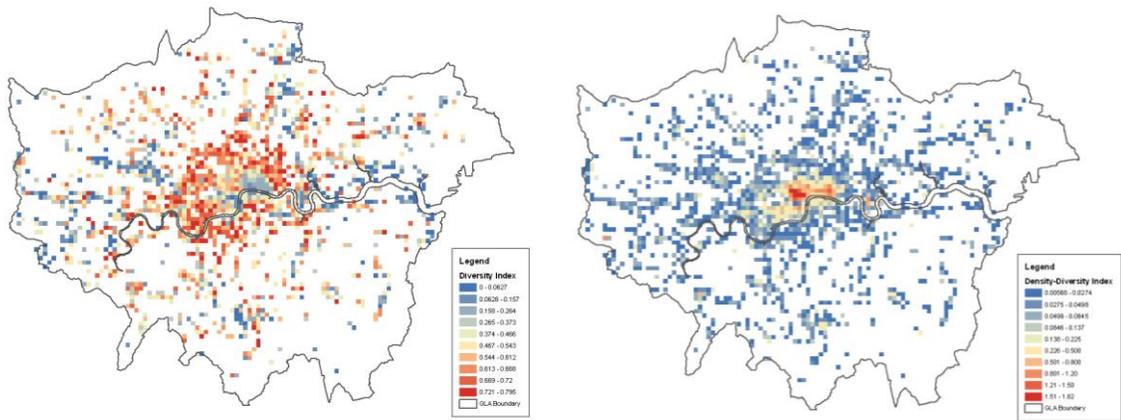
Figures 5.30 & 5.31: Diversity/Functional-Balance Index (left) and Density-Diversity Index (right) for Rateable Value of Functional Super-Groups. Data Source: VOA 2005.

5.3.3   Statistical Analysis of Real-Estate Centralisation and Clustering

It is clear from the density and diversity analyses that location patterns are highly distinct between urban functions. Here we use the methodology from Chapter 4 with centralisation and clustering indices to analyse the degree of monocentricity or polycentricity in the different real-estate functions, as shown in Table 5.12. The Office group is by far the most clustered and the most centralised (over 75% of all office floorspace is located within Inner London), emphasising a highly monocentric pattern for office activities. Retail is also relatively centralised (45% of floorspace in the inner-city) and clustered, though

less so than office activities. This reflects some dispersion towards local centres for retail activities. Both the Retail and Office groups feature a significant increase in rateable value clustering compared to floorspace, in addition to an increase in centralisation. Essentially this means that the high value office and retail activities are clustered, and the most valuable clusters are in the city centre. In contrast to this highly centralised pattern, the Industrial and Supermarket groups are much more decentralised, reflecting bid-rent processes which push high floorspace low-value uses out of the city centre (discussed in Chapter 2), and their attraction to automobile accessible areas for bulk goods transport. Industrial uses show some moderate clustering, reflecting business park location patterns, while supermarkets are extremely dispersed. In contrast to the Office and Retail groups the floorspace and rateable value results are very similar. Therefore Industrial and Supermarket groups do not gain significantly in value from locating centrally, and this explains their avoidance of expensive central locations. The non-bulk classes contain rateable value results only. Generally the leisure orientated groups are highly centralised and clustered, while the local and public service orientated groups are less clustered and only moderately centralised.

Table 5.12: Floorspace and Rateable Value Spatial Indices by Functional Group. Data Source: VOA 2005.

Functional Group	Clustering Index[1]		Centralisation Index[2]	
	Floorspace	Rateable Value	Floorspace	Rateable Value
Office	4.724	7.021	0.77	0.85
Retail	1.003	3.822	0.45	0.61
Supermarket	0.276	0.237	0.24	0.25
Industrial	0.616	0.597	0.27	0.24
Factory	0.661	0.65	0.17	0.19
Local Services	-	1.255	-	0.57
Leisure	-	4.679	-	0.70
Restaurant	-	4.537	-	0.71
Education	-	0.609	-	0.47
Health	-	1.019	-	0.56
Emergency Services	-	0.337	-	0.61
Hotel	-	5.653	-	0.85

[1] Getis-Ord General G statistic using linear inverse distance function, threshold 800m. Results *1000 to improve legibility.

[2] Proportion of floorspace/rateable value within the inner city, as defined by 2004 London Plan (GLA, 2004).

Another approach to exploring this data is to plot the centralisation and clustering indices together in a manner similar to the monocentricity-polycentricity diagram developed in Chapter 4 (Sub-Section 4.6.3). In this plot monocentric forms appear in the top-right of the diagram whilst polycentric forms appear in the top-left. As can be seen in Figures 5.32 and 5.33 high clustering is strongly associated with high centralisation and polycentric distributions (as defined here) are not found for any of the functional groups in the Greater London study area. The variable that comes closest is Retail floorspace. Monocentric forms in contrast are common for many of the rateable value measures (reflecting the high value of Central London), whilst dispersed-decentralised distributions characterise the Industrial and Supermarket groups. Public services tend to gravitate towards the centre of the diagram, reflecting a balanced central place hierarchy distribution.
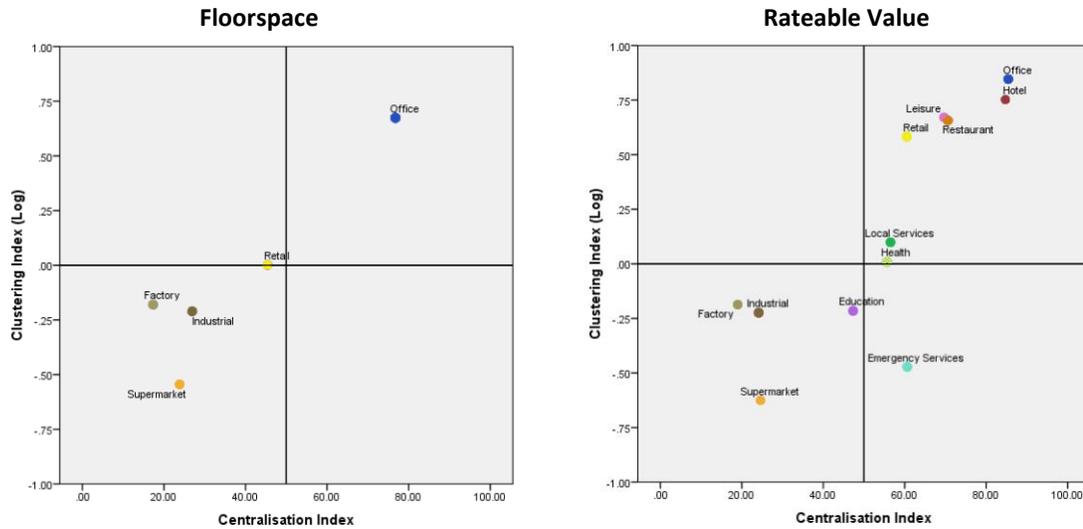
Figure 5.32 & 5.33: Centralisation and Clustering Index Plots for Functional Group Floorspace (left) and Rateable Value (right).

5.3.4   Real-Estate Value: Estimating Rent

In the theoretical discussion in Chapter 2 we advocated the importance of property market data for understanding urban land uses and identifying agglomeration economies. As estimate of commercial rents can be calculated by taking the ratio of rateable value to floorspace from the VOA data. This indicator is mapped for the Office function group in Figure 5.36 and in the

Retail function group in Figure 5.37. Note the same classification is applied to both maps to aid comparison. For office activities the highest values are unsurprisingly in the City of London and the West End, with the very highest rents in Mayfair. This results confirms evidence from direct rental surveys used for the London Office Policy Review (Greater London Authority, 2007b). This result corresponds to the strong agglomeration economies in the city centre and generally matches an Alonso-type monocentric model of urban land use as described in Chapter 2. Complicating the simple monocentric pattern however, there are corridors of higher value rents, Moderately high rental values spread west and north from the city centre, particularly to the west through the boroughs of Kensington and Chelsea, Fulham, and towards Heathrow. A select few business parks around Heathrow are of very high rents comparable to Central London (e.g. Stockley Park in Figure 5.32). This is likely due to their high specification and the benefit of good motorway and airport accessibility. In general the Outer London centres identified in the previous floorspace density analysis, such as Croydon, Bromley and Romford, are of low rental value. Centres close to the Western Corridor, such as Uxbridge, have moderately high rents, while Wimbledon and Richmond seem to be uniquely attractive small-scale centres.
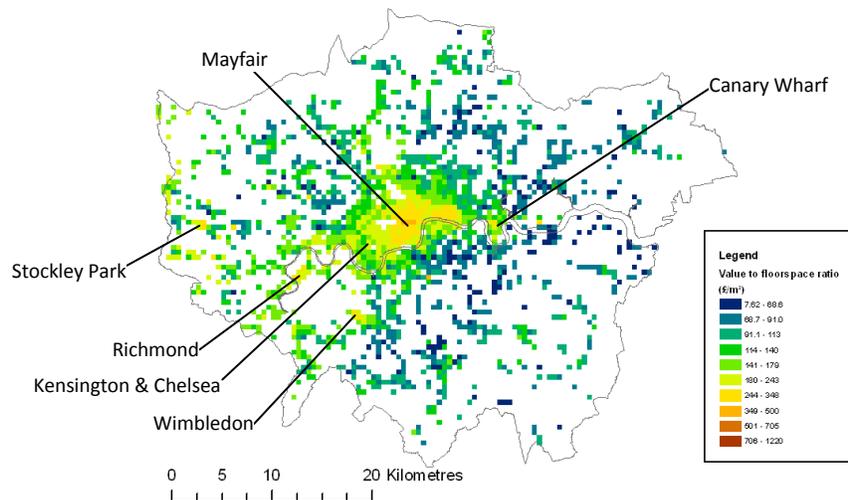
Figure 5.34: Rental Value Proxy for Office Function Group. Data Source: VOA 2005.

It is clear from visual analysis that there are connections between office rental costs and the employment specialisation measures discussed in Section 5.2.

Theoretically this confirms the arguments from Chapter 2 that high rents and occupational specialisation will be found in areas of strong agglomeration economies. Demand for such areas will be high from businesses looking to benefit from these positive externalities, and consequently rental costs will rise. The relationship is graphed at ward level in Figure 5.35, producing a moderately strong regression R^2 of 0.45. Note that there are statistical reservations with the use of percentage/ratio variables in regression, as discussed further in Section 6.3.2. When the model residuals are mapped (Figure 5.36) it is clear that the model is under-predicting for the most prominent central and west-central clusters, implying a non-linear relationship. There also appears to be an element of prestige missing, with affluent centres to the west having higher rents than those predicted by the model. Overall it is a significant result that the different dimensions of employment specialisation- occupational class, sectoral specialisation and rental value- are closely linked geographically.
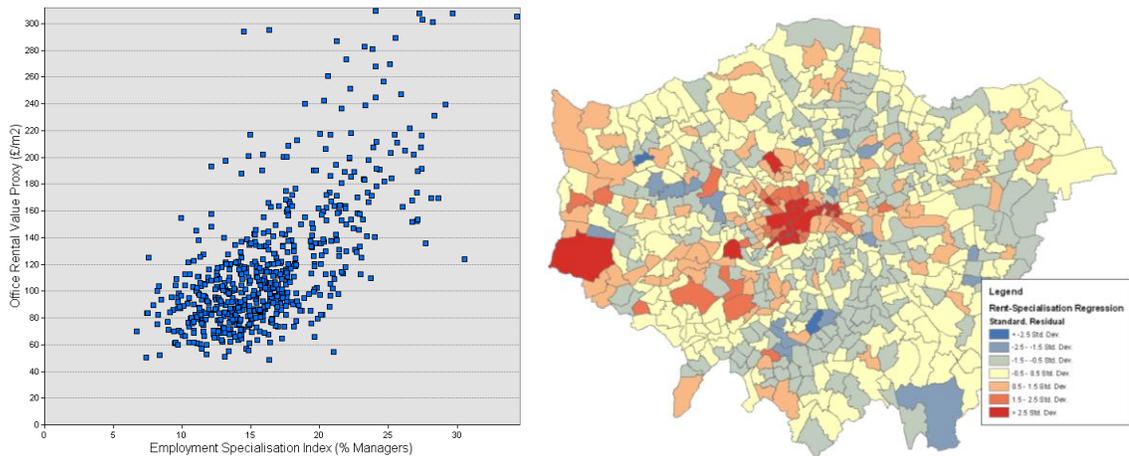
Figure 5.35 & 5.36: Office Rent Proxy and Employment Specialisation Graph (left) and Regression Analysis Residual Map (right).

The spatial pattern in the rental proxy measure for the Retail function group is broadly similar to the Office group, though this has several distinct features, as shown in Figure 5.37. Firstly the range of variation is higher for retail activities, with the highest retail costs reaching over £1200/m², which is more than twice as high as the most expensive office costs per unit floorspace. Secondly the highest retail values are more tightly confined to central areas such as the West End and Knightsbridge. The high value centres in Outer London do not

correspond to the high retail floorspace density centres identified in the previous analysis (such as Croydon and Kingston) but instead relate to smaller affluent centres, such as Wimbledon and Richmond, and to a lesser extent Ealing and Bromley.
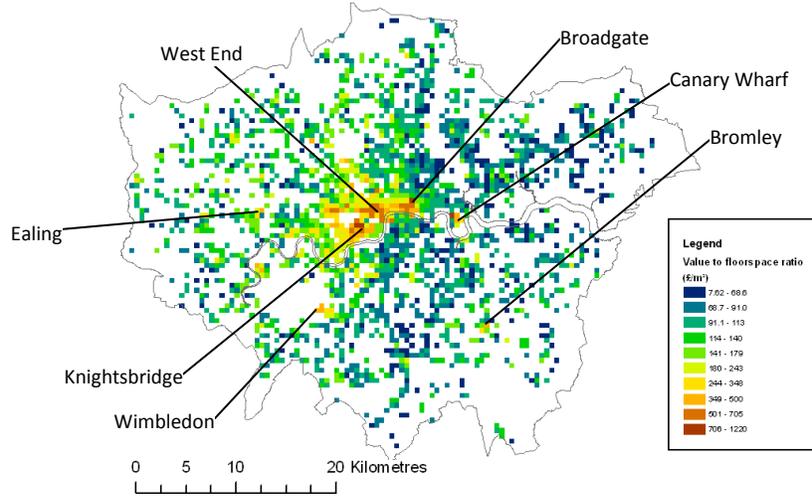
Figure 5.37: Rental Value Proxy for Retail Function Group. Data Source: VOA 2005.

In summary, rental costs overall reflect the highly centralised Greater London pattern. There is a moderately strong correlation between rental costs and the employment specialisation measures described in Section 3.2, providing evidence for the link between specialised agglomeration economies and increased demand for office space. Furthermore there is an additional prestige element in rental costs that inflates both office and retail rents in small attractive centres particularly to the west. Meanwhile the largest Outer London centres such as Croydon and Bromley have relatively low rents. This undermines any simple relationship between density and rental value, with development restrictions in attractive historic centres pushing up rental values.

5.3.5   Real-Estate Dynamics: London Development Analysis

The theoretical discussion in earlier chapters stressed the importance of urban dynamics, and it is necessary to augment the previous static real-estate analysis with consideration of real-estate dynamics and how the structure of London is changing. As VOA business rates data was only available for 2005, planning completions data from the GLA has been used for the dynamic analysis. As part of monitoring programme to assess progress towards policy targets set in the

London Plan, the Greater London Authority set up a London Development Database in 2000. This database integrates planning completions data from the 33 London boroughs for major commercial developments of over 1000m² in total floorspace. The following analysis is based on all non-residential permissions completed between the years 2000-2009[1].

To assess the spatial and functional pattern of urban development in the last decade, two main measures are used: total new floorspace completed, i.e. all new space resulting from completed permissions, and total net floorspace completed, i.e. all new floorspace minus any floorspace lost from previous buildings demolished. The trends are summarised at sub-regional level for Greater London in Table 5.14. The clear pattern is the intensification of Central and Inner London, together accounting for 38.7% of all net floorspace expansion, and a massive 74.9% of office growth. Net industrial floorspace has declined in the city-centre and inner-city, to be replaced mainly with office (and residential) functions. The Central Activities Zone (CAZ) alone accounts for 48.1% of office growth.

---

[1] Any developments granted permission before 2000 (though completed after) will be missing from this dataset. The functional classification is based on the standard UK planning use class orders. These are similar to the functional groups used to classify the VOA data above and can be linked together as shown in Table 5.13. Permissions information in the database includes location data, and this has been used to spatially reference the data in the same manner as the VOA real-estate database (see Sub-Section 5.3.1). There are a total of 2,657 permissions, which is a relatively small total compared to the 100,000's of premises in the VOA data.

Table 5.13: Mappings Between Functional Groups and Use Classes

Functional Group	Use Classes
Office	B1
Retail	A1
Industrial	B2, B8
All	A1, A2, A3, A4, A5, B1, B2, B8, C2, D1, D8, Sui-Generis

Beyond the inner-city, development patterns are comparatively modest, and are significantly uneven between the outer sub-regions. The North-Eastern sub-region includes several major development sites including the Royal Docks and parts of the Thames gateway. The Western sub-region also has relatively high development levels, particularly for office functions. The Northern, South-Western and South-Eastern sub-regions show much lower levels of development activity. Overall this indicates relative development stagnation in many parts of Outer London. This pattern can be linked to the previous analysis of commercial rent geography, as high rents are the main profit incentive for development to take place.

Table 5.14: Floorspace Completed by Greater London Sub-Region 2000-2009.
Data Source: London Development Database.

Sub-Region	Functional Group							
	Retail		Office		Industrial		All	
	Total (000's m²)	Net (000's m²)	Total (000's m²)	Net (000's m²)	Total (000's m²)	Net (000's m²)	Total (000's m²)	Net (000's m²)
City Centre (CAZ)	288	134	4,493	1,690	24	-205	5,606	1,945
Inner-City	244	209	1,194	941	191	-106	2,489	1,504
North	151	115	111	75	261	139	941	654
North-East	256	232	349	300	633	273	1,920	1,393
South-East	137	121	202	43	378	257	1,260	779
South-West	133	94	270	115	353	64	1,281	648
West	172	128	535	347	876	284	3,132	1,995

The spatial pattern of development can be considered in greater detail by mapping the completions data. The changes in office and retail floorspace are shown in Figures 5.38 and 5.39, using the same classification system as the previous VOA analysis. Two major patterns stand out: the intensification of the City of London and the continued spectacular expansion of Canary Wharf. Following a series of problems in the early 1990's, Canary Wharf experienced a boom period during the 2000's, with many new high-rise buildings including massive new headquarters for HSBC and Barclays banks. The other major area of office expansion is the City of London. This covers a much larger area than Canary Wharf and is linked to expansion in the neighbouring City Fringe.
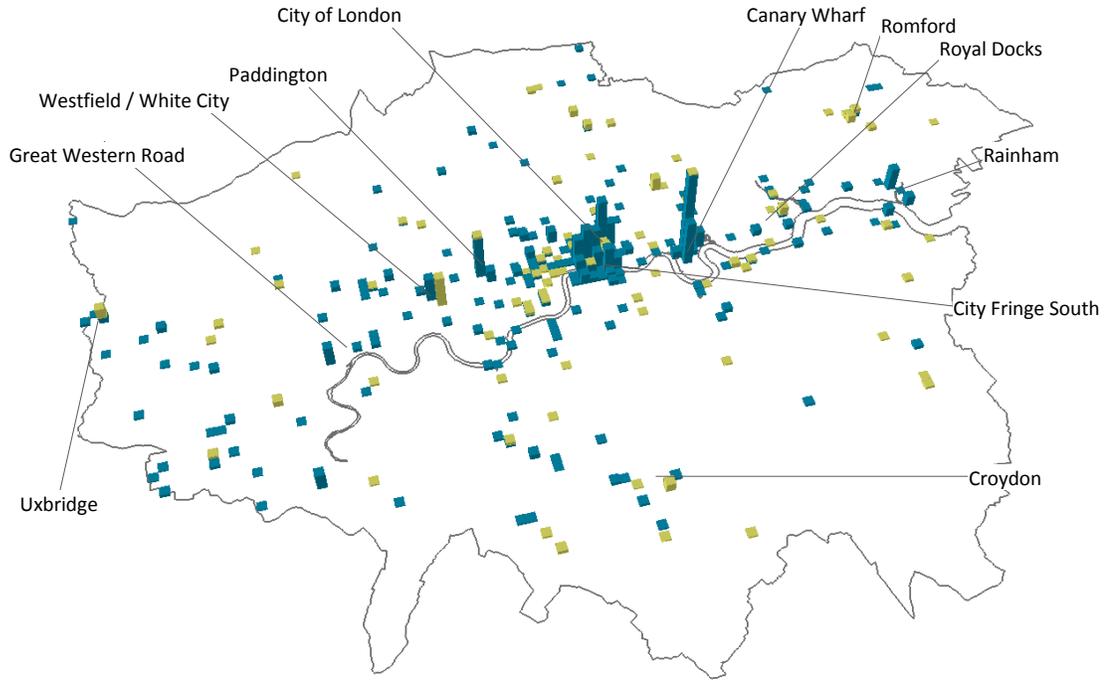
Figure 5.38: Net Floorspace Gain from Office and Retail Completions 2000-2009.
Data Source: London Development Database.
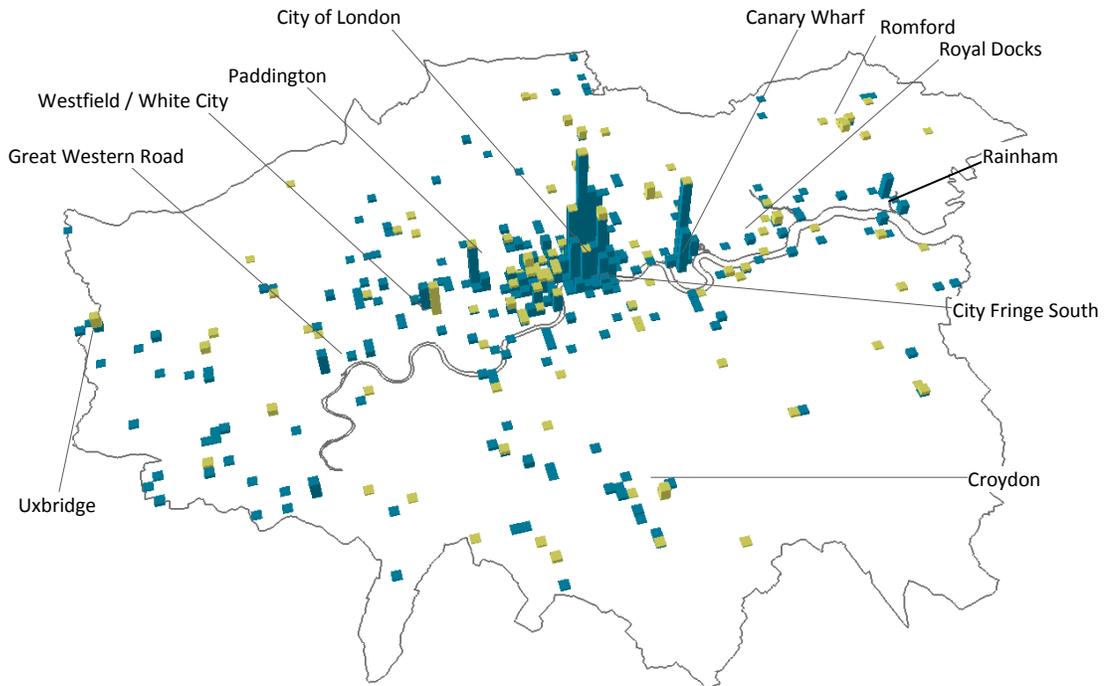
Figure 5.39: New Floorspace from Office and Retail Completions 2000-2009.
Data Source: London Development Database.

Much of the development in the City has replaced existing office space, and so the total floorspace expansion is significantly larger than the net expansion, as can be seen by comparing Figures 5.34 and 5.35. This is also the case for the West-End of Central London which has seen much more modest intensification compared to the City of London.

There are two additional inner-city clusters of development to the west at Paddington and White City, both large-scale brownfield sites identified for major expansion in the London Plan (Greater London Authority, 2004). Indeed overall the patterns of development show the success of planning policy in managing new development towards the city-centre and to high density clusters at public transport nodes. This pattern is set to continue into the 2010's with new clusters at Stratford and Kings Cross. The expansion of more dispersed less accessible sites, such as the business parks around Heathrow Airport, appears to have been largely curbed by planning policy during the last decade (although there is some expansion around Heathrow and Great Western Road). Furthermore the Thames Gateway eastern corridor policy can be seen in sites such as Rainham. The greatest concern from a strategic planning viewpoint is the distinct lack of activity in the Outer Metropolitan centres. Locations such as Croydon, Bromley and Ilford have little development activity, which implies economic stagnation. Croydon has only modest activity despite its labelling in the London Plan as an opportunity area for expansion. This Outer London stagnation (except for the west) trend matches the previous employment change and specialisation analyses in Section 5.2, and the rental analysis in the previous sub-section, with both demand and supply indicators reflecting low growth.

In addition to office and retail development, there is also significant development activity in other functional classes (Figure 5.40). The largest single completion is Heathrow Terminal 5 with a gigantic 550,000m² of floorspace (over 6% of the London total between 2000-2009). Wembley Stadium is another large-scale single development. The other significant change comes from the inclusion of industrial developments, which are mainly clustered in the eastern Thames corridor.
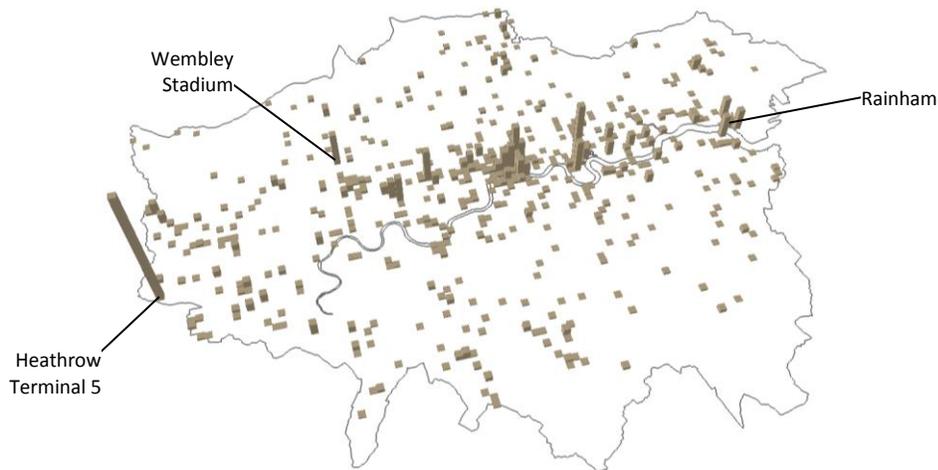
Figure 5.40: New Floorspace from All Completions 2000-2009.
Data Source: London Development Database.

A theme that runs through recent patterns of growth in London is 'mega-development' with many very large-scale developments (Greater London Authority, 2009). Beginning with Broadgate and Canary Wharf in the 1980's, this trend is evident in the Paddington and White City clusters that have grown in the last decade. This represents a unification of trends in private sector real-estate development towards greater economies of scale (with increasing large-scale international investments) and current planning policies encouraging high density brownfield nodal development around public transport interchanges. Furthermore current planning permissions point to mega-developments continuing, as shown in Figure 5.41. These include the 2012 Olympic site at Stratford, and a number of high profile developments based around mainline rail termini, such as at Kings Cross and Waterloo. It remains to be seen how many of these schemes will progress given the recent economic crises. Canary Wharf has been at the frontline of the financial turmoil, with major tenants of Lehman Brothers and Bear Stearns now in administration. Proposals for expansion here are on hold, and similar delays are occurring at other developments.

Figure 5.41: Planning Permissions for 'Mega-Development' Schemes.
Source: Greater London Authority (2009).

5.3.6   Summary

Real-estate data provides a distinct empirical perspective for the analysis of intra-urban employment geography and the built-environment. The results highlight very strong clustering patterns of commercial real-estate, with specific density, function and rental profiles for London's urban core, tertiary centres, metropolitan centres and Western Corridor. The three key measures of function, density and rental value are interrelated with high densities generally associated with high value and diversity. These relationships are indicative of the property market processes and agglomeration economies described in the earlier theoretical chapters, with high value locations attracting development. Detailed relationships relate to the specific type of employment centre, its place within the metropolitan region, issues of prestige and planning constraints.

Overall Greater London displays a strong monocentric pattern. Office activities are overwhelmingly agglomerated in the city centre and inner-city with a weak market in Outer London, as confirmed by clustering, centralisation, density and

rental value analysis. The Outer London market is strongest in the western radial corridor, taking the form of mono-functional business park developments. Retail activities follow a more dispersed, central-place hierarchical pattern with a select number of Outer London centres functioning as significant retail centres. The data on urban development over the last decade shows the existing centralised structure is intensifying, with the vast majority of office growth within the inner-city. London Plan policies have been largely successful in achieving significant central expansion and directing growth towards public transport nodes, although development stagnation continues across Outer London. The high density clustering of development has resulted in the trend of brownfield site mega-developments, including several inner-city sites in similar vein to Canary Wharf. This represents a more localised polycentric development within Inner London and the travel implications of such developments are explored in Chapter 6.

5.4   Chapter Conclusions

This Chapter set out to answer Research Aim 5i, which is to assess the spatial structure of economic activities in London at an intra-metropolitan scale, and assess to what extent these activities can be considered polycentric. The analysis of employment geography has revealed stark agglomeration processes operating at intra-metropolitan scales in the study region, leading to highly uneven patterns in employment growth, urban development and specialisation. There are simultaneous processes of centralised and decentralised growth occurring in the study area, both reproducing the historic monocentric pattern in Greater London and creating an interconnected polycentric urban region, thus undermining any straightforward interpretation of the London region as either monocentric or polycentric.

The methodological approach developed in Chapter 4 has been successful in analysing and quantifying the intra-metropolitan employment geography processes occurring in the study region. The multiple dimensions of employment specialisation, including occupational class, sectoral specialisation and growth, have been shown to be closely related, and furthermore correlated

to property market rents. This latter relationship highlights how agglomeration economy processes drive built-environment change as discussed earlier in Chapter 2. These high rents incentivise property investment, and correspond to the urban development patterns measured in the real-estate analysis, particularly through the growth of city centre. This link between rent and development is not entirely straightforward however as it is managed by urban planning. Planning policy in London seeking to redirect growth from west to east and cluster development on brownfield sites, with mixed results as discussed below.

The dynamics of the post-industrial economy in the London Region closely fit with urban theory discussed in Chapter 1, with strong business service, financial and tourism growth. These trends have overwhelmingly benefitted Central and Inner London which captured over 50% of Greater London jobs growth between 1991 and 2001, and an astonishing three quarters of new Greater London office floorspace in the last ten years. Returning to the concept of multiple centres with unique locational advantages, Central London is highly attractive to high-density knowledge economy clusters, and its growth has been greatly facilitated through planning policy. Yet in addition to this monocentric growth pattern, the analysis has also identified the growth of decentralised knowledge economy clusters in particular sectors, with IT and Defence industries strongly clustered in the Western Sector, and Media and Television activities in the Western Corridor. The attraction of these locations includes airport and motorway accessibility, lower rental costs, and the cumulative feedback from the co-location of related industries over several decades. This is in addition to more general back-office trends and suburban locations in many service industries that have boosted regional growth. The net effect is that growth rates outside of the GLA boundary consistently exceed Greater London, and there are comparable absolute increases in OMA employment to the Greater London total. Additionally the volume of regional journey-to-work interactions is also increasing, particularly in the form of reverse commuting. These trends strongly support the polycentric urban theory from the earlier literature review, and we must conclude that at the regional level monocentric and polycentric trends in employment geography are occurring simultaneously, with location trends segmented by industrial sectors and functional specialisations.

The combined analysis of socio-economic geography and built-environment dynamics means that supply and demand in property markets can be analysed together and used to inform policy. The aim of the London Plan in concentrating development at public transport nodes has been successful, marrying compact city type policy with the market demand for business service growth. Inner-city nodal development at major public transport interchanges has largely united planning policy and demand, with Canary Wharf spurring on further expansion at Paddington and White City, and future development at Stratford and Kings Cross. The more negative side of the coin in London's volatile economy is that continuing manufacturing decline and restructuring in service industries has led to job losses in many parts of Outer London. Even during the boom years, planning policy failed to achieve significant growth in Outer London centres, such as the opportunity area of Croydon. Rents are low and there appears to be little market demand for expansion. Arguably greater policy attention could have encouraged new activities to locate in Outer London centres. There is an element of 'zero-sum game' in property development, where the allocation of urban development to the inner-city will lessen demand elsewhere (Greater London Authority, 2009). The market bias towards Central and West London does create a significant barrier. Furthermore the lack of regional control beyond the GLA boundary is problematic as trends increasingly see Outer London compete with more successful centres in the wider South East.

Looking ahead to the final chapter, this analysis of employment geography has raised a series of issues in terms of relationships with patterns for accessibility and travel sustainability. The intra-metropolitan variation in employment specialisation and growth dynamics is likely to be driving changes in regional journey-to-work patterns. It is important to profile the various economic activity centres in terms of their travel sustainability performance, and to question whether planning policy is guiding growth towards appropriate locations. The performance of the city centre, expanding centres in the wider region and inner-city nodal clusters is of particular importance given current growth patterns.

Chapter 6

Accessibility, Journey-to-Work Patterns and Travel Sustainability in the London Region

Building on the analysis of employment geography in the previous chapter, we now turn our attention to travel sustainability and consider the London region in terms of accessibility and trip patterns. We assess both the geography of potential interaction, i.e. accessibility, and actual interaction using journey-to-work data. Overall, there are two key aims of this chapter specified in the thesis introduction. The first (Research Aim 5ii) is to profile the London region journey-to-work patterns at an intra-metropolitan scale based on the key dimensions of travel sustainability identified in Chapter 3. These dimensions are mode-choice and travel distances, and we take the further step of combining these measures using the CO_2 emissions indicator specified in Chapter 4. The scale of analysis is a central consideration, and here regional summary analysis is combined with more detailed intra-metropolitan mapping analysis. This approach allows differences in travel patterns between the many intra-urban centres in the London region to be assessed, and provides evidence for the monocentric-polycentric sustainability debate at the specific level of urban activity centres.

The second aim of this chapter is to identify the underlying causes of intra-urban travel variation, and in particular the relationships between journey-to-work patterns and employment geography (Research Aim 5iii). We argued in Chapter 3 that accessibility and socio-economic variables are the major influences on travel behaviour, whilst built-environment variables such as density are essentially proxies for accessibility, and these arguments are tested for the study area. Furthermore it was also indicated in Chapter 3 that employment geography is

likely to play a significant role in determining travel patterns, and this is assessed using the employment specialisation indicators developed in Chapter 5. A series of multivariate regression analyses are undertaken in this chapter, including a comprehensive set of accessibility, socio-economic and built-environment variables to test the theoretical arguments for the London region. Several significant relationships are revealed using this approach.

The chapter begins by examining the outputs from the mode-specific accessibility model in Section 6.1, which allows the calculation and mapping of accessibility indices for the London region. Section 6.2 links the accessibility model to journey-to-work data and provides a regional overview of mode-choice patterns, travel distances and the commuting links between London and the wider region. This overview is the foundation for a set of more detailed analyses of the dimensions of sustainable travel, with mode-choice considered in Section 6.3, travel distances in Section 6.4, and the combined CO_2 emissions indicator in Section 6.5. These sections include mapping and multimodal regression analyses where the urban travel sustainability theory and relationships with employment specialisation variables are tested.

6.1   Mapping Public and Private Transport Accessibility

The conclusions from the earlier review chapters argued that accessibility is central to the functioning of cities and is a critical variable in understanding urban land use and travel patterns. This section presents the accessibility model for calculating network based travel times for public transport and car modes in the study area. The accessibility model methodology was outlined earlier in Chapter 4, and here this methodology is applied in the specific context of the London region. Results are explored through mapping analysis with the intention of highlighting accessibility contrasts between modes.

6.1.1   The London Region Accessibility Model

Accessibility varies temporally and spatially, and subsequently it is necessary to define the spatial and temporal scope of the model. The focus here is on journey-to-work analysis, and consequently network characteristics are measured for the

AM peak period of 7-9am. Spatially the model area is defined as the Greater South East Region. While the study analysis area is smaller than the Greater South East (as defined in Sub-Section 6.2.1), problems of edge effects and external trips can be minimised by modelling the transport networks of a larger area. The main innovations in the measurement of accessibility used here are the detailed network geography modelled for each mode, with average speed information included, and multi-model public transport trips allowed. These properties address the recommendations from Chapter 3 on methods to improve the accuracy of accessibility measures.

How transport modes are differentiated is a fundamental decision for accessibility modelling. Here public transportation modes are modelled in an integrated fashion whilst private transport is modelled separately. Public transport trips in London are often multi-modal, with combinations of mainline rail, underground, light rail and bus commonplace. This is in addition to pedestrian stages of public transport journeys. Therefore the public transport accessibility model treats public and pedestrian transport in an integrated manner allowing interchanges. This requires a particular database and interchange algorithm structure as detailed in Appendix E. A limitation of the model is that it does not allow car-public transport multi-modal trips to be directly represented. For example a trip involving driving to a rail station would instead be represented as a bus/cycle/walk trip to the rail station.

The second innovation in the accessibility model is the use of detailed speed information on network links to allow more realistic representation of travel times. Congestion is a very significant influence on travel times in large cities such as London. A number of recent GPS-based data sources measuring actual road performance can be used to calculate average link speeds. Transport for London (TfL) have provided GPS-derived data for this research (Transport for London, 2005). The data records average travel properties on links during a period of one month, May 2007, with a total of 1.38 million link observations over the AM peak period. This is a large enough survey to provide speeds for a comprehensive network of major routes in Greater London. The ITIS data is a rich source from which to calculate road journey times in the study area. It does

not however include journeys beyond the M25. Another GPS data source, Ecourier data, has been used for the major roads in the Outer Metropolitan Area, and has been calibrated against the TfL data. This process is detailed in Appendix E. The resulting road network average speeds are shown in Figure 6.1.
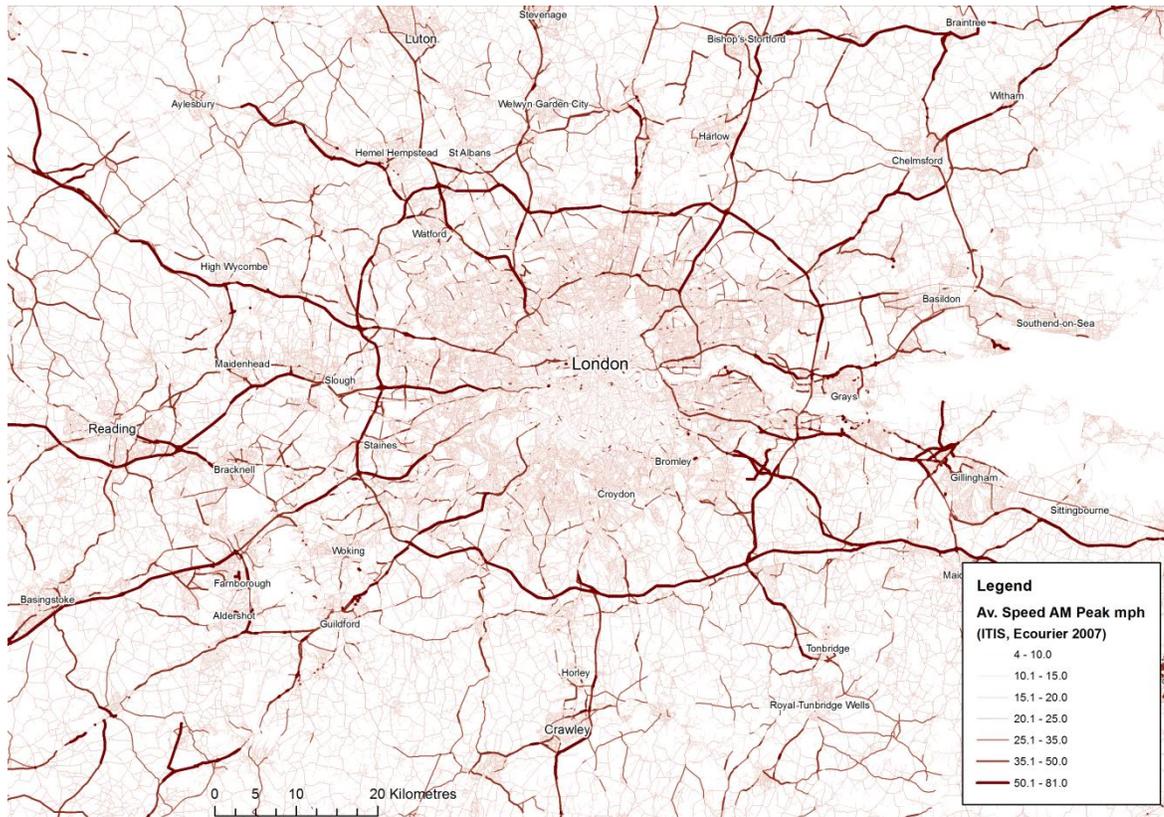
Figure 6.1: Greater London Average Road Speeds, AM Peak. Data Sources: ITIS Holdings 2007, produced by TfL Road Network Performance; Ecourier 2007; Ordnance Survey 2007b.

Congestion trends in the London region are clearly highlighted in Figure 6.1, with widespread spatial variation in the performance of roads. The anticipated general pattern of increasing congestion towards Central London can be clearly seen, as can a number of further trends. Within Central London the arterial road hierarchy concept effectively breaks down, with low speeds on nearly all routes. The North Circular Road functions as an Inner London bypass, though with bottlenecks clearly visible. An equivalent bypass to the south is conspicuously absent, likely with accessibility consequences for South London centres such as Croydon. The motorway network appears to operate relatively well with average speeds above 50 mph, though some sections of the London orbital

motorway slip below this figure. Speeds on the A-road network are noticeably higher in Outer London and the wider South East, particularly to the west where the dense motorway and A-road network provides high car accessibility.

For measuring speeds on public transport networks a combination of timetable and spatial analysis methods are used (see Appendix E). The rail network is based on average timetabled speeds for morning peak services, as illustrated in Figure 6.2. Note that the speeds are service-specific and there can be several services with different speeds on the same line. Figure 6.2 maps the fastest service on each line. Timetables are also the basis of calculating wait times for interchanges on both the rail and underground networks. The most weakly modelled mode is the bus network, which is not timetable-based due to the volume and complexity of services. Instead a proxy network based on bus stop locations and density is used (see Appendix E).
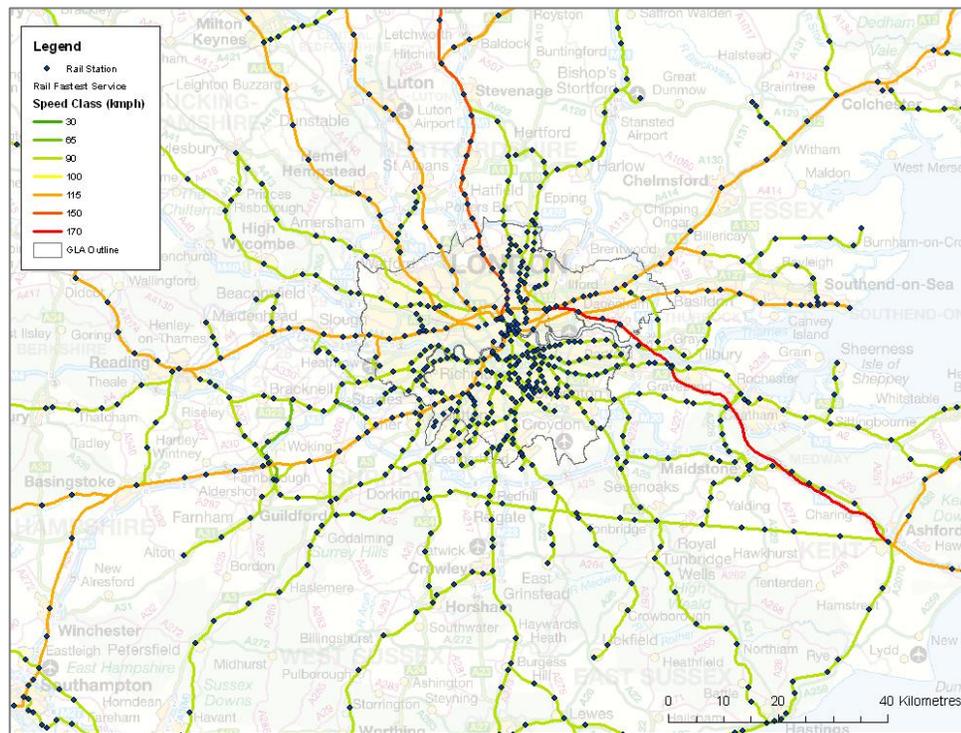
Figure 6.2: Mainline Rail Network, with Speeds of Fastest Services.
Data Sources: Ordnance Survey 2007c; NPTDR 2010.

6.1.2 Public and Private Transport Accessibility to Central and Outer London Destinations

In this section we visualise the results of the accessibility model with the aim of highlighting intra-metropolitan contrasts in public transport accessibility and car accessibility. We begin by examining accessibility to Central London. Due to the radial nature of London's public transport networks, Central London has by far the highest public transport accessibility. This is highlighted in Figure 6.3 which shows travel times to Kings Cross (including the entire journey of walk time, wait time and interchange time). Inner London locations are all accessible within 45 minutes or less, and the majority of Greater London in 80 minutes or less. Furthermore towns with direct rail services to Kings Cross, such as Stevenage and Luton, are well connected with travel times of around one hour. Generally the pattern of public transport corridors is clearly visible on the map.
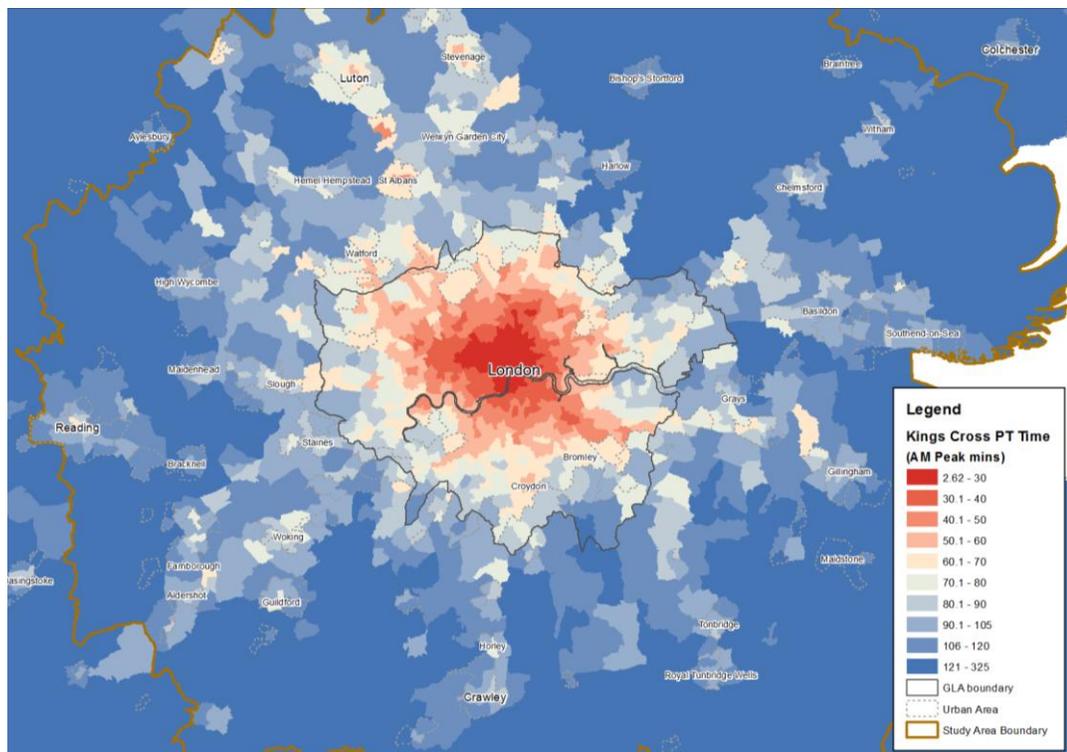
Figure 6.3: Public Transport Travel Time to Kings Cross (AM Peak, ward Scale).

Travel times by car to Kings Cross provide an interesting comparison, as shown in Figure 6.4. Again radial corridors are evident, this time corresponding to motorways and A-road dual carriageways. Accessibility south of the Thames is

weaker. Generally travel times compare favourably with the public transport times, except for more distant rail connected towns such as Luton and Reading. Caution must be taken however in making direct travel time comparisons between the car and public transport results, as the travel time accessibility measure does not include important road costs such as car parking. Parking is highly restricted and expensive in Central London and would limit the kind of car accessibility shown in Figure 6.4.
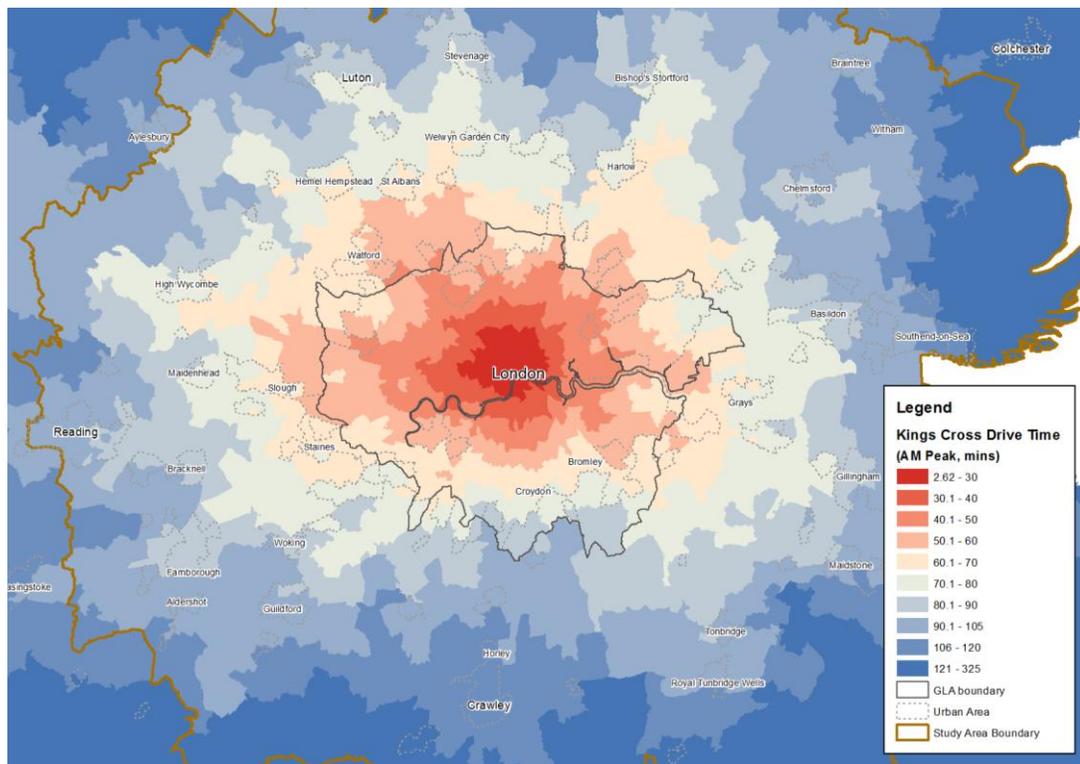
Figure 6.4: Road Travel Time to Kings Cross (AM Peak, ward scale).

A more dramatic contrast between car and public transport accessibility can be found by analysing a destination in the wider region beyond Greater London. Travel times from Reading are shown by public transport in Figures 6.5 and by car in Figure 6.6. Here public transport access is confined to a narrow radial corridor extending to Central London, whereas road accessibility extends to a large area of the wider South East, with the whole Western Sector accessible within typical commuting thresholds. This is the basic accessibility pattern that underpins the contrasting radial public transport and dispersed road transport city archetypes discussed in Chapter 1, and furthermore has clear links to the mode-choice behaviour in the study region, analysed in Section 6.2 and 6.3.
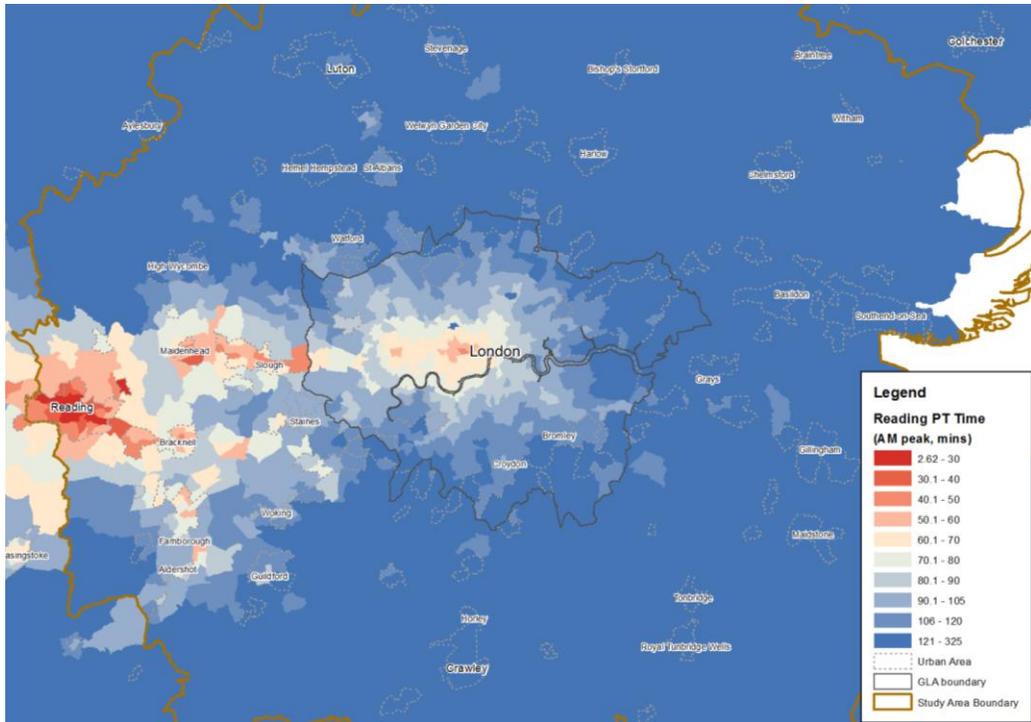
Figure 6.5: Public Transport Travel Time to Reading, AM Peak.
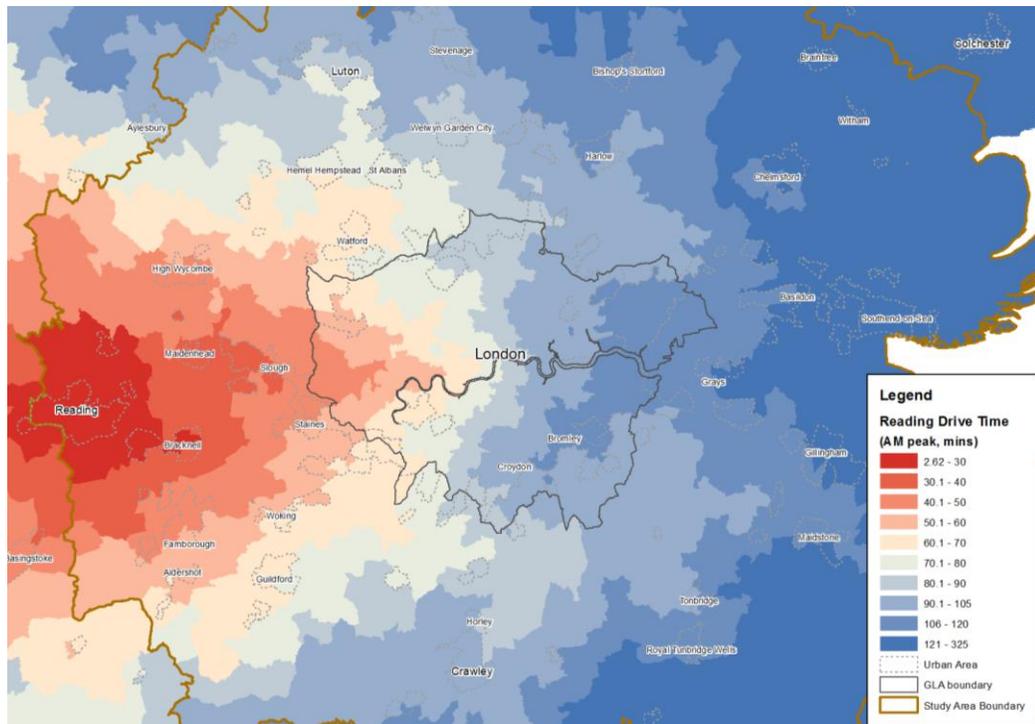
Figure 6.6: Road Transport Travel Time to Reading, AM Peak.

In addition to selecting individual origins or destinations, a rich perspective on accessibility comes from analysing the full matrix of origins and destinations simultaneously, using a measure such as the Hansen Index introduced earlier in Chapter 4. The results of the Hansen Index for public transport and road accessibility, using residential population as the opportunity and a distance decay parameter value (x) of 1.5, are shown in Figures 6.7 & 6.8. High public transport accessibility is confined to Central and Inner London, and tails off rapidly in Outer London. In contrast, high road transport accessibility is considerably more dispersed across the region, with good accessibility found near the intersections of radial motorways and the M25 orbital motorway. This high road accessibility is likely to be playing a significant role in the regional growth areas such as the Western Sector identified in Chapter 5. Note that the lower growth area of East London does not suffer from significantly poorer accessibility by these measures, so it does not appear to be accessibility that has restricted growth here (although there is the issue of accessibility to specific facilities, such as Heathrow, that benefits West London). In fact it is South London that has the major road accessibility disadvantages.
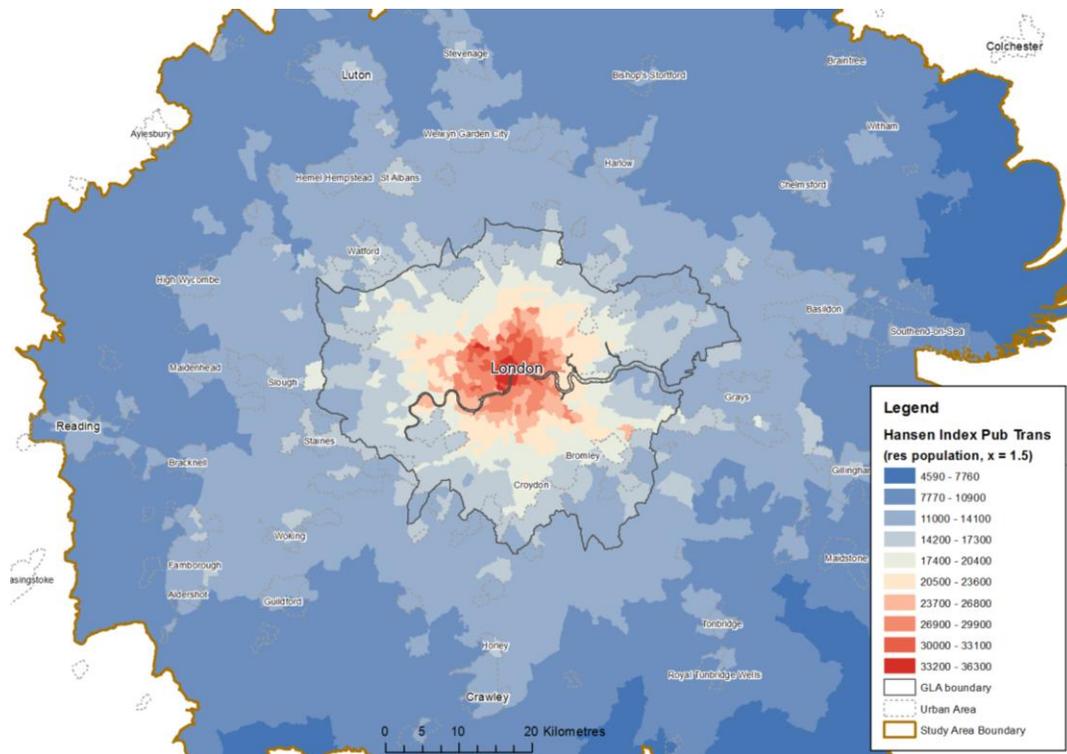
Figure 6.7: Public Transport Accessibility to Residential Population Hansen Index
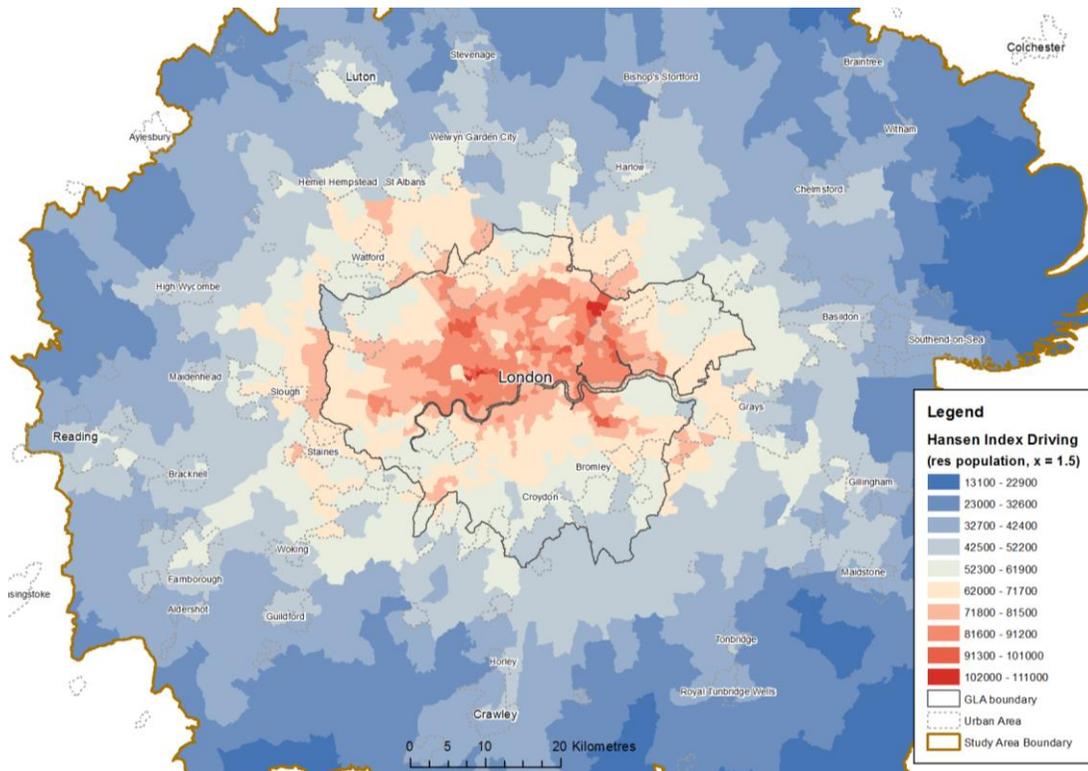
Figure 6.8: Road Transport Accessibility to Residential Population Hansen Index

6.1.3   Summary

The accessibility model developed focuses on the AM peak period for journey-to-work analysis, and allows multi-modal public transport journeys. The accessibility mapping results highlight the restricted nature of the public transport network in the study area, with high accessibility confined to Central and Inner London. This contrasts with the road network where high accessibility is considerably more dispersed, with Outer London and the wider region defined by superior levels of road access to public transport access. This accessibility pattern is linked to the employment growth trends shown in Chapter 5 and furthermore is closely connected to mode-choice behaviour, as examined in the following sections.

6.2 Overview of Journey-to-Work Patterns in the London Region

There is rich spatial variation in journey-to-work patterns, and this variation can be analysed at a range of scales. We begin here with an overview of trends in terms of regional connections, mode-choice and the time profiles of trips. These analyses provide the foundation for the finer-scale and more in-depth modelling of intra-urban mode-choice and trip distance patterns in Sections 6.3-6.5. In Chapter 5 we highlighted significant growth trends occurring beyond the GLA boundary and the increasing travel links between Greater London and the wider region. Here we analyse travel relationships between Greater London and the South East in more detail, and use this analysis to define the London region study area on a Functional Urban Region basis. Next we provide an overview of mode-choice patterns, which are critical in travel sustainability relationships. Finally we consider the time and distance profiles of journey-to-work trips by different modes, highlighting aspects of mode-choice behaviour.

6.2.1 Regional Commuting Connectivity to London and the Study Area Boundary

As discussed previously, Greater London is a global business centre with approximately 4 million jobs and is the central hub of a complex multi-modal transportation network. This is reflected by dense networks of commuting flows within Greater London and the surrounding region. Commuting patterns are the traditional basis for defining Functional Urban Regions, and this approach is used here to define the wider study area for the travel sustainability analysis. The proportion of employees who work in Greater London is mapped for the wider region in Figure 6.9 using 2001 Census data. The pattern is generally one of linear decline with distance from the GLA boundary, with some interesting variations on this trend. Firstly it is apparent that a considerable proportion of residents in Outer London are travelling to jobs beyond the GLA boundary, with some zones showing over 20% of travel to the wider South East. Indeed this pattern of reverse commuting is the fastest growing type of flow across the GLA boundary (see Sub-Section 5.1.5) and is a strong indicator of increasing interactions between Greater London and the wider region.

A low proportion of commuting to Greater London from towns in the wider region is indicative of greater sub-regional employment opportunities. Larger towns to the north and west, such as Reading and Luton, show relatively low commuting proportions to Greater London of around 10%. This contrasts with towns to the east, such as Southend and Gillingham, where flows to London are between 10-30%. This pattern is connected to the sub-regional employment geography described in Chapter 5 with a greater number of jobs in more specialised industries in the Western Sector compared to the relatively weaker and more isolated sub-region to the east of Greater London. This east-west division is overlain on further patterns in relation to distance from Greater London and settlement size, with smaller settlements less economically independent. These patterns affect variation in trip distances, as analysed in Section 6.4.
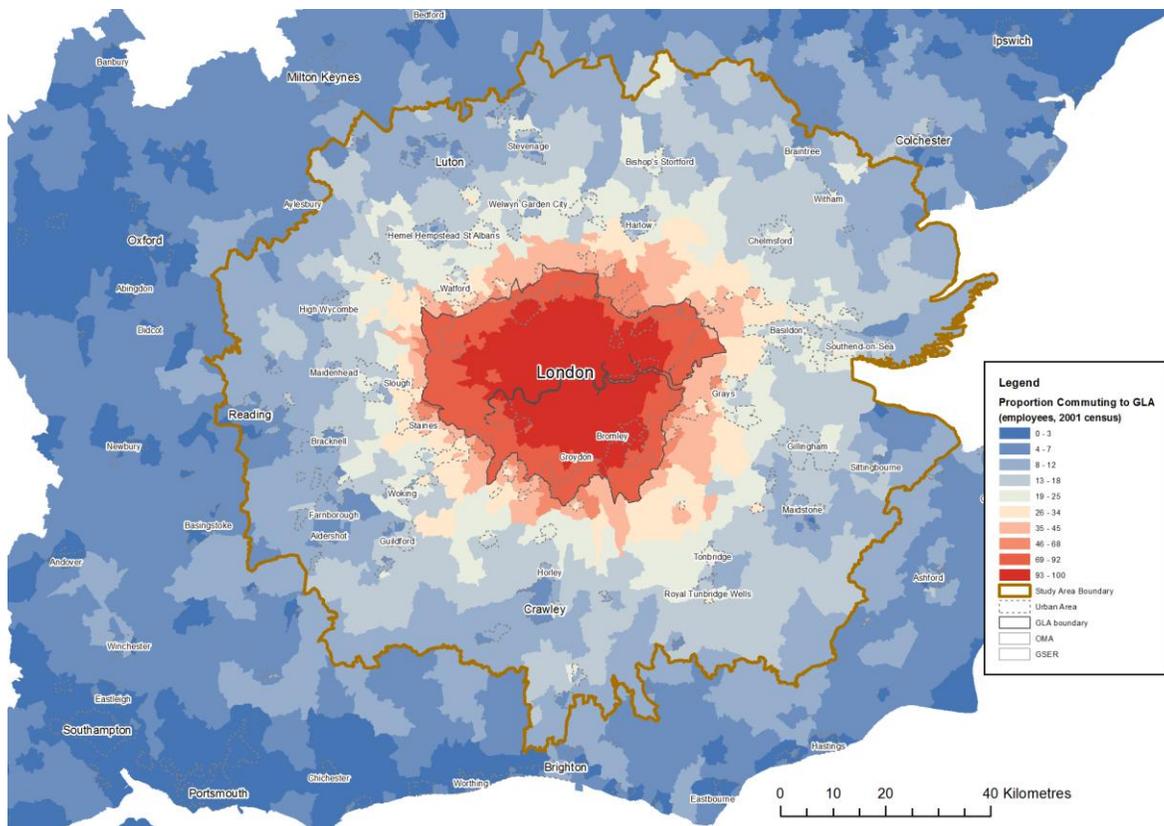
Figure 6.9: Proportion of Employees by Residence Commuting to Greater London. Data Source: Census 2001 (ONS, 2010b).

The orange study area boundary line in Figure 6.7 marks the extent of the study region defined for the travel sustainability analysis. Henceforward the area beyond Greater London and within the study area boundary is referred to as the Wider Study Area. The study region boundary is based on a 10% commuting threshold to Greater London, with minor manual adjustments to ensure a contiguous area. The intention is to include surrounding settlements in London's immediate influence with a direct relationship expressed in the journey-to-work data. The boundary is very close to the Outer Metropolitan Area concept used in Chapter 5. More distant cities such as Oxford and Ipswich are considered to be sufficiently independent in terms of daily travel to be excluded. Note that Brighton and Colchester are just below the 10% threshold, and arguments could be made both for and against their inclusion in the study area.

Flows to Greater London are only one dimension of the complex sub-regional commuting patterns that exist over the wider South East. We can explore these trends by mapping the flows between all wards across the Greater South East, as shown in Figure 6.10. As can be seen, London is the central star in an intricate galaxy of interactions. Furthermore there are many additional sub-centres at various scales attracting their own commuting catchments. Larger cities at distances of 100 km or more- such as Southampton and Ipswich- are separate from London in commuting terms with their own distinct functional regions. There are examples of nearby towns that appear to be 'paired' together by commuting flows, such as Gillingham and Maidstone, and particularly Crawley and Brighton. We can speculate that the latter relationship relates to job opportunities in Crawley at Gatwick airport, combined with an attractive living environment in Brighton. The high degree of commuting to London from eastern towns is clearly visible. The Western Sector shows stronger economic independence and more local connections, particularly Reading. Additionally Heathrow Airport is a major sub-centre pulling in employees from across the region. Outer London town centres, such as Croydon, are barely discernable due to the larger overlapping flows to Central London.
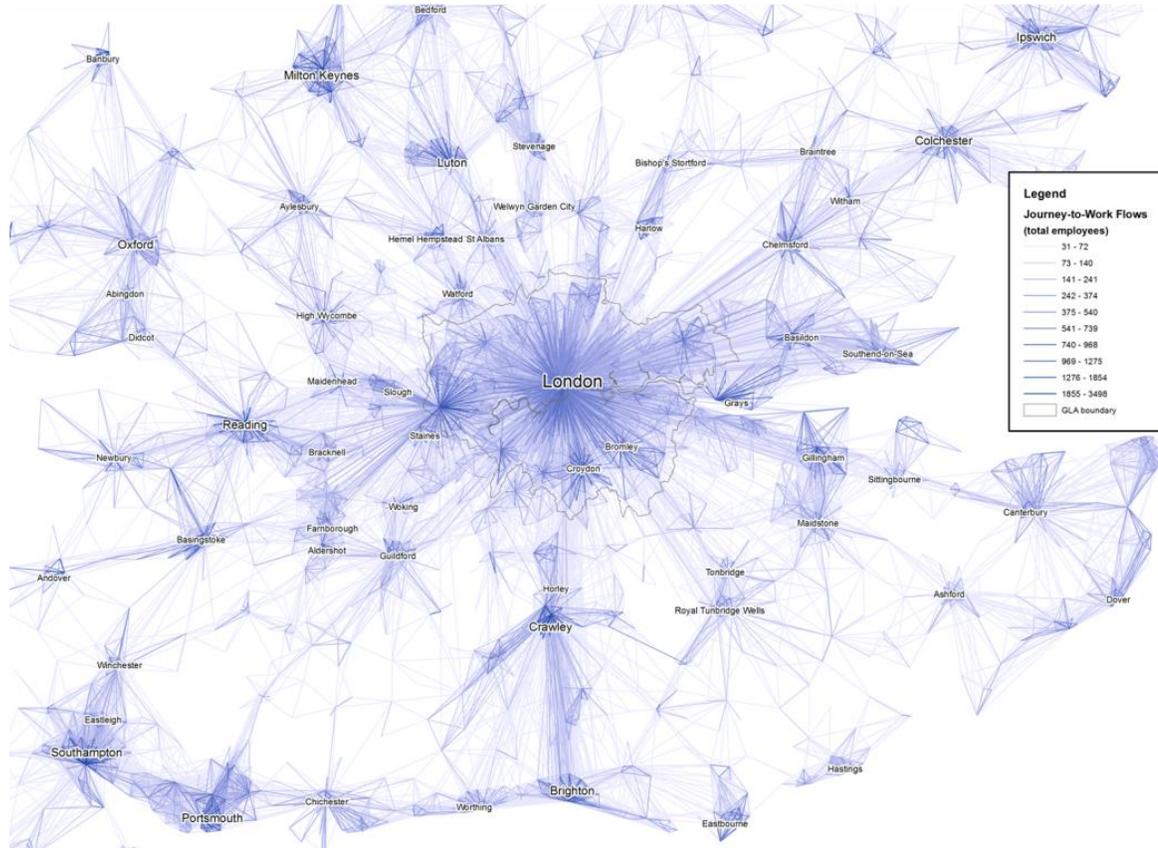
Figure 6.10: Commuting Flows in the Greater South East Region.
Data Source: Census 2001 (ONS, 2010b).

Overall this analysis has shown the complex interconnections between London and the surrounding region. The widespread commuting flows across the GLA boundary strongly support the regional approach of this research. There is no definitive means of establishing exactly where the wider study region boundary should fall, and a 10% commuting threshold has been applied here. Finally east-west variations in flows indicate the importance of sub-regional employment accessibility in journey-to-work patterns, which is further explored in Section 6.4.

6.2.2   Mode-Choice at Sub-regional Level

Mode-choice has highly significant implications for the efficiency and environmental impacts of transportation systems (see Chapter 3). Here we analyse mode-choice patterns for journey-to-work in the study area at regional and sub-regional scales. The 2001 UK census records the main mode for

journey-to-work and this is summarised for Greater London residents in Figure 6.11 and for Greater London plus Wider Study Area residents (as defined in the previous sub-section) in Figure 6.12.
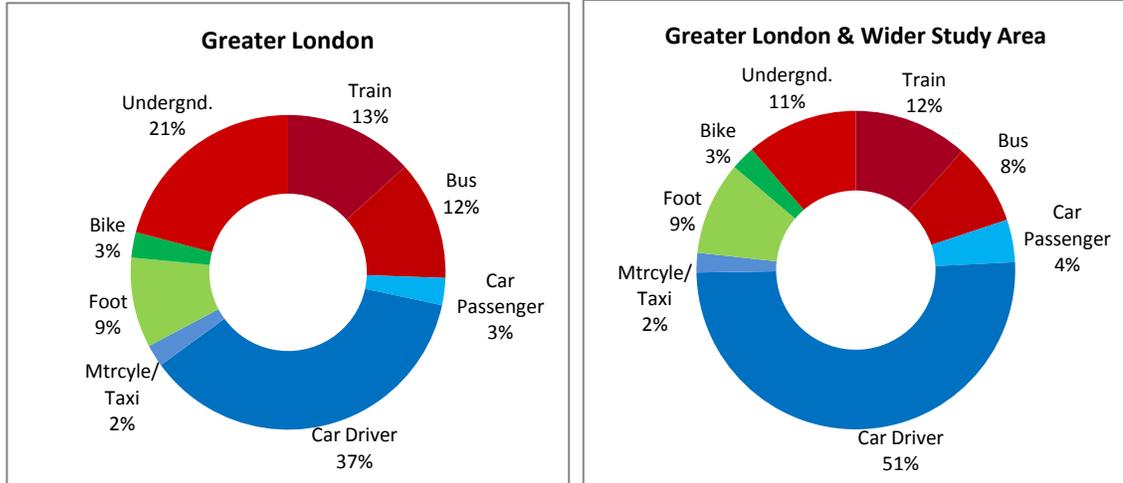
Figures 6.11 & 6.12: Journey-to-Work Main Mode-Choice from Residents in Greater London (left) and Greater London plus the wider region (right).
Data Source: Census 2001 (ONS, 2010b).

Within Greater London the majority of commuting journeys are by public transport (46%), while private motorised travel also represents a very large proportion of trips (41%). The London Underground is the most popular public transport mode, while private motorised trips are overwhelmingly dominated by Car Driver (i.e. mainly single occupancy) trips. The 'active' transport modes of walking and cycling are marginal, although walking is a supplementary mode in all public transport trips. Mode-choice patterns for the Wider Study Area unsurprisingly have a greater car focus, with 56% by private motorised modes, and again Car Driver trips dominate. The proportion of train trips is very similar to Greater London, while underground falls by nearly half. Interestingly the proportion of active travel is near identical, indicating that smaller towns show similar proportions of pedestrian and cycle trips to Greater London. Note that only a single 'main mode' is recorded in the UK census (Frost and Spence, 2008). Any supplementary modes, such as a bus or underground journey to or from a rail station, are not included. Supplementary modes in public transport journeys can however be estimated using the integrated multi-modal

accessibility model discussed in Section 6.1, and this approach is used later in the CO_2 indicator analysis.

We now consider sub-regional spatial variation in mode-choice patterns. A summary matrix is presented in Figure 6.13, including the sub-region location of journey-to-work origins and destinations. The trip flow totals used to compile the summary diagram are detailed in Appendix F. As can be seen both the origin and destination locations of trips have a highly significant influence on mode-choice decisions, even at this relatively coarse scale of sub-regions. The anticipated general pattern of public transport dominance in Central and Inner London can be seen, giving way to private transport dominance in Outer London and the wider region.
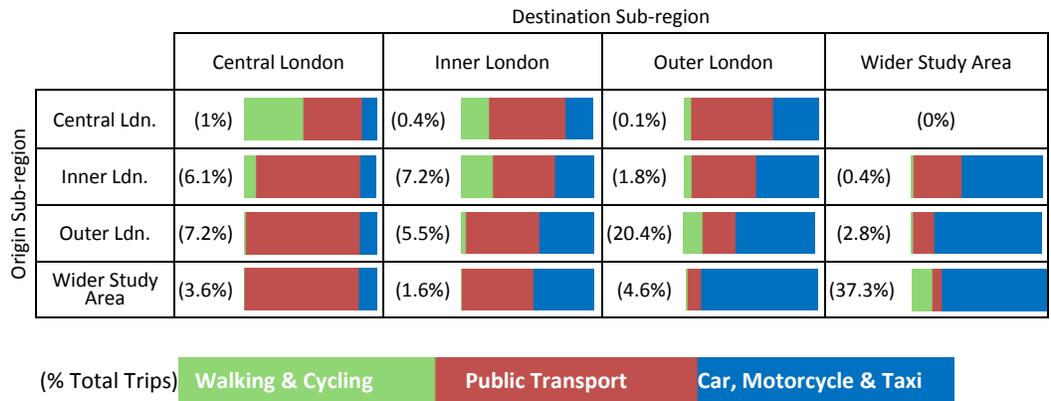
Figure 6.13: Summary of Journey-to-Work Mode-Choice Between London Sub-regions. Data Source: Census 2001 (ONS, 2010b).

Central London and to a lesser extent Inner London minimise car travel when they are the destinations for commuting trips, due to high congestion and parking costs in combination with strong public transport access. This trend is moderated for the reverse commuting case when residents of the Central and Inner sub-regions travel outwards for work, as a greater proportion of car trips can be seen in these cases. Walking and cycling trips are restricted to internal flows within sub-regions. Central London in particular displays high active travel at 45% of trips. Generally Outer London and the Wider Study Area are similar in their trip characteristics, indicating that Outer London has functionally much in common with areas beyond the GLA boundary. This is significant as the majority of trips occur in Outer London and the Wider Region,

with their internal flows representing 20.4% and 37.3% of all trips respectively, explaining why for the region as a whole the car is the most frequent mode.

In summary, the mode-choice analysis shows that in basic terms Central and Inner London journey-to-work trips are dominated by public transport and pedestrian travel; Outer London is evenly split between public and private transport; and beyond the GLA boundary the car dominates. These overall patterns have clear implications for the monocentric-polycentric sustainability debate, though further analysis on trip distances and finer-scale variation need also to be considered before reaching conclusions. The sub-regional travel patterns indicate that there will be strong relationships between accessibility and mode-choice, an assumption analysed statistically in Section 6.3. Another important issue highlighted is the importance of both trip origins and trip destinations in influencing mode-choice, as issue which was highlighted in the Chapter 3 review. Whilst both are influential, it appears that in the Central and Inner London context the destination sub-region is particularly significant, likely connected to very high car travel costs in these areas. Again this is explored further in Section 6.3.

6.2.3   Distance, Travel Time and Mode-Choice

In this sub-section we take the journey-to-work mode-choice patterns described above and consider their characteristics in terms of distance and time. This analysis describes the types of journeys travellers prefer to make (or are willing to endure) to facilitate their residential and workplace location preferences. To calculate distance and time for journey-to-work trips, the accessibility model from Section 6.1 is combined with the journey-to-work flows by mode. The model assumes that commuters choose the quickest route between their origin and destination ward using the main-mode recorded in the UK Census 2001. The journey-to-work trip distances are graphed in Figure 6.14, showing a clear distance decay pattern, as commuters generally prefer to make shorter trips. The mean trip length is 17 km and varies by mode with short walking and cycling trips, and long distance public transport travel, as shown in Table 6.1.
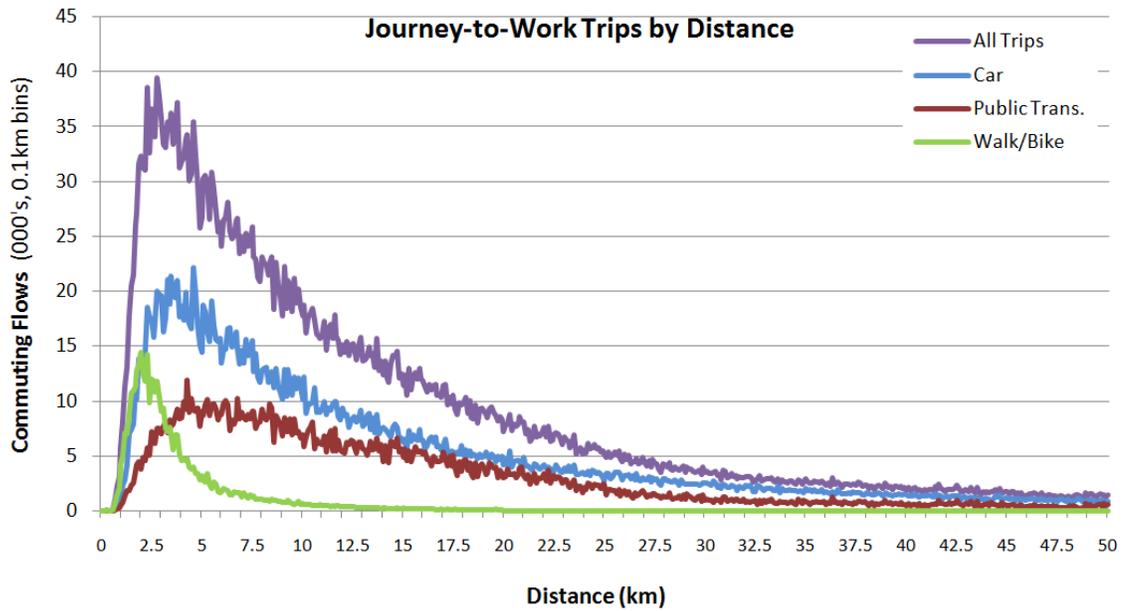
Figure 6.14: Journey-to-Work Trips Distance Histogram.

Table 6.1: Journey-to-Work Trip Cost Properties by Mode

Transport Mode	Distance (entire trip)		Time (entire trip)	
	Mean (km)	Mode (0.1 km bins)	Mean (mins)	Mode (1 min bins)
Walking	3.38	2	40.56	24
Cycling	5.73	2.9	22.92	12
Bus	7.63	4	42.78	35
Underground	12.46	8	50.89	45
Rail	25.97	14	69.20	60
Car	19.13	4.6	38.62	17
All Trips	17.04	2.8	45.00	31

The accessibility model allows the calculation of travel time for journey-to-work trips as shown in Figure 6.15. Travel time provides greater insight into travel behaviour as it is much closer to perceptions of travel cost than distance (see Section 3.2). The travel behaviour patterns that underlie the time-profiles in Figure 6.15 are a consequence of variations in mode speeds, other trip costs such as monetary and softer factors, as well as additional factors such as car parking that restrict certain types of journey. Active travel is slowest and is

generally perceived as high cost, resulting in lower than average trip times (the mean trip time for all journeys is 45 minutes). Car travel is made over similar distances to public transport, though is calculated as being significantly faster in the model results. It is interesting to speculate whether this is because car travel is simply quicker and more competitive for many journeys, or whether public transport is perceived as being lower cost (in terms of money and/or softer factors) and thus longer duration travel is more bearable. The accessibility analysis in Section 6.1 strongly supports the former competitiveness argument, with public transport accessibility restricted to radial trips and as a result being slower than the car for the majority of journeys.
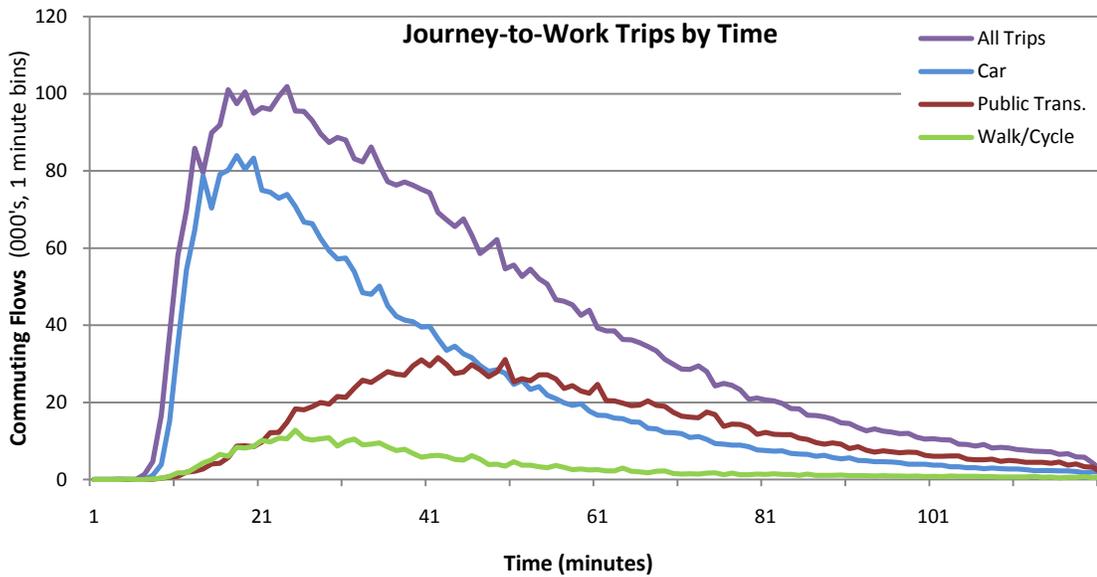
Figure 6.15: Journey-to-Work Trips Time Histogram.

Public transport travel can be further broken down into individual modes as shown in Figure 6.16. Mainline rail is by far the longest distance mode. This trend is likely connected to rail being the only realistic option for long-distance commuting to Central London, as well as potentially favourable characteristics of rail travel in terms of ability to read/work while travelling (although overcrowding diminishes this). Note that there is likely an element of over-prediction of travel time for rail trips, as wait times are estimated as half of the service headway in the model. Regular commuters minimise this wait time for reliable timetabled rail services.
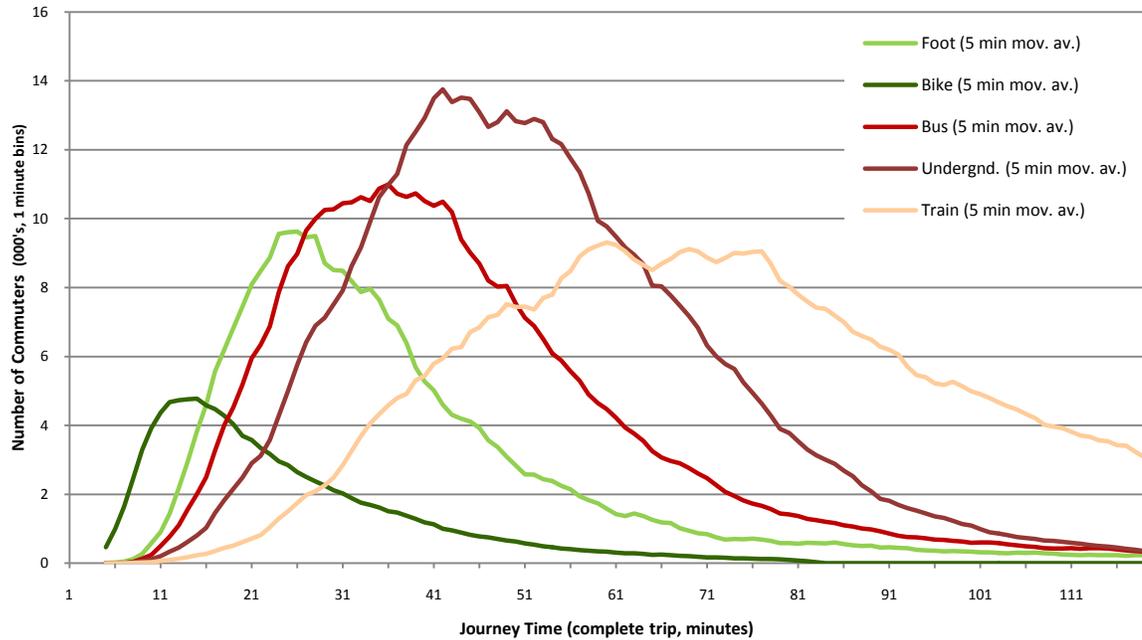
Figure 6.16: Journey Time Trend Lines for Public Transport and Active Modes.

6.2.4   Summary

The analysis of journey-to-work trips has highlighted London's context in a wider region of travel flows, and emphasised the need for a regional perspective in any comprehensive travel sustainability analysis. These connections vary significantly across the South East and are related to employment geography patterns, as explored further in Section 6.4. The sub-regional mode-choice analysis identified distinct travel profiles for Central and Inner London, Outer London and the Wider Study Area, indicating strong relationships between accessibility and mode-choice and trends towards less sustainable mode-choices beyond Inner London (discussed in the next section). Finally the analysis of trip times by mode indicates the superior competitiveness of the car for many journeys across the region, and the long duration of many public transport work trips, particularly by rail.

6.3   Mode-Choice Analysis

The following sections analyse the major characteristics of journey-to-work patterns in relation to travel sustainability. Mode-choice is considered here, followed by trip distances in Section 6.4 and finally an integrated indicator of travel CO_2 emissions in Section 6.5. This section builds on the previous mode-choice overview with a more detailed geographical and statistical analysis of mode-choice relationships, focussing on the factors that increase and decrease the proportion of car journey-to-work trips. We begin by mapping mode-choice patterns. This is followed by multivariate regression modelling to analyse the multiple factors that influence mode-choice decision making. In the earlier theoretical discussion in Chapter 3 it was proposed that accessibility and socio-economic factors (such as car ownership) are the core determinants of mode-choice. In this section we test these hypotheses statistically for the study area.

6.3.1   Mapping Mode-Choice by Trip Origin and Destination

Mode-choice patterns can be mapped to residential origin and workplace destination zones as shown in Figures 6.17 and 6.18. The distinction between spatially referencing trips to origins and destinations is highly significant as there are widespread changes in the spatial distribution of public transport trips between these maps (the figures have the same legend classification to aid comparison). Moderately high proportions of public transport journeys originate across Greater London and the Wider Study Area, extending along major rail corridors. It can be seen from the contrasting employment destination map that these trips overwhelmingly end within Greater London, and indeed largely end in Central and Inner London. Employment centres beyond the Greater London boundary are generally highly car based (more than 70%). This conclusion is confirmed by Figures 6.19 and 6.20 which map the proportion of car trips by origin and destination. These maps are essentially the inverse pattern of the public transport maps. Very low proportions of orbital and reverse commuting occur by public transport, confirming the earlier sub-regional analysis in Sub-Section 6.2.2.
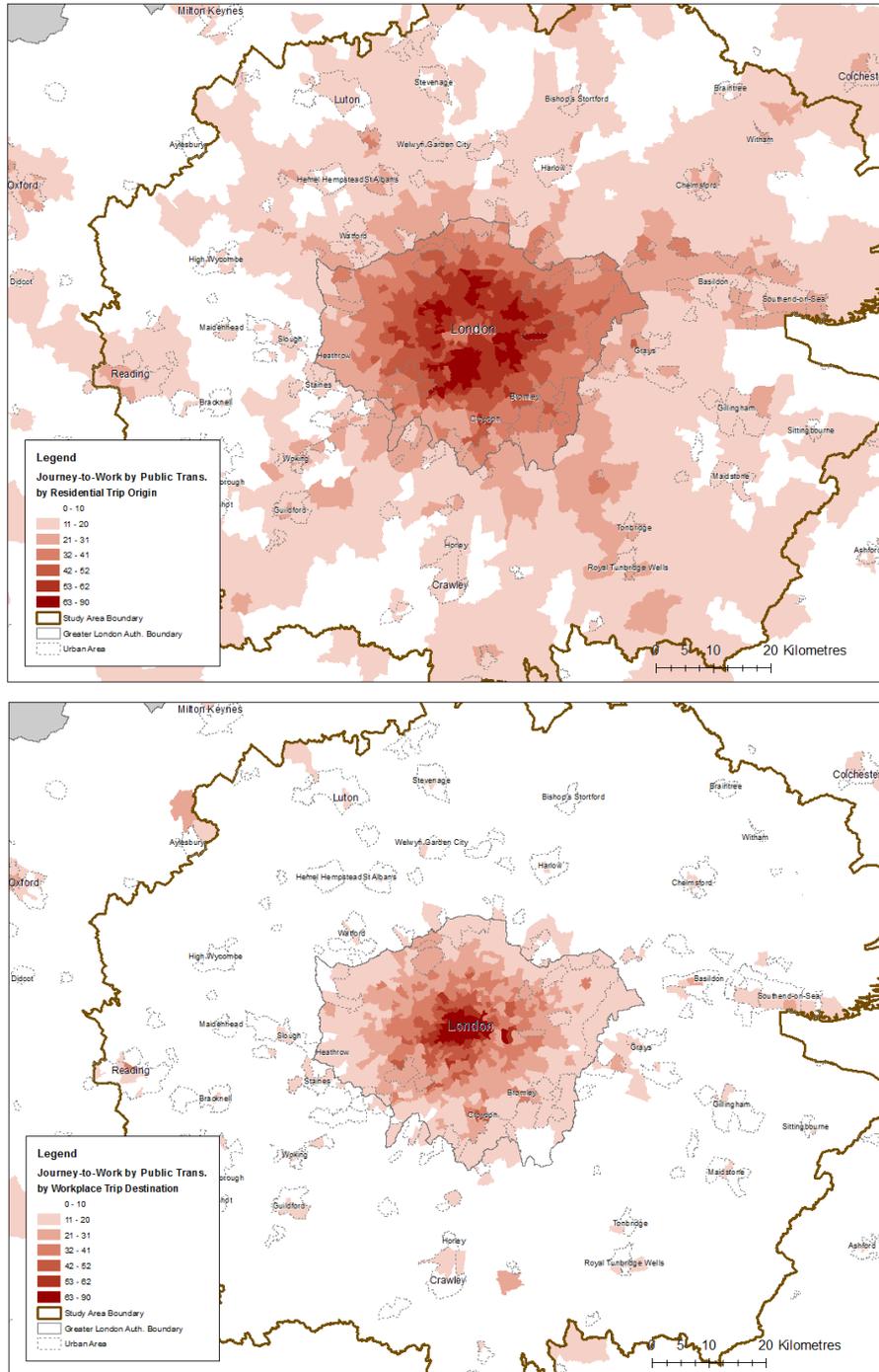
Figure 6.17 & 6.18: Journey-to-work by Public Transport Percentage by Trip Origin (above) and Trip Destination (below). Data Source: Census 2001 (ONS, 2010b).
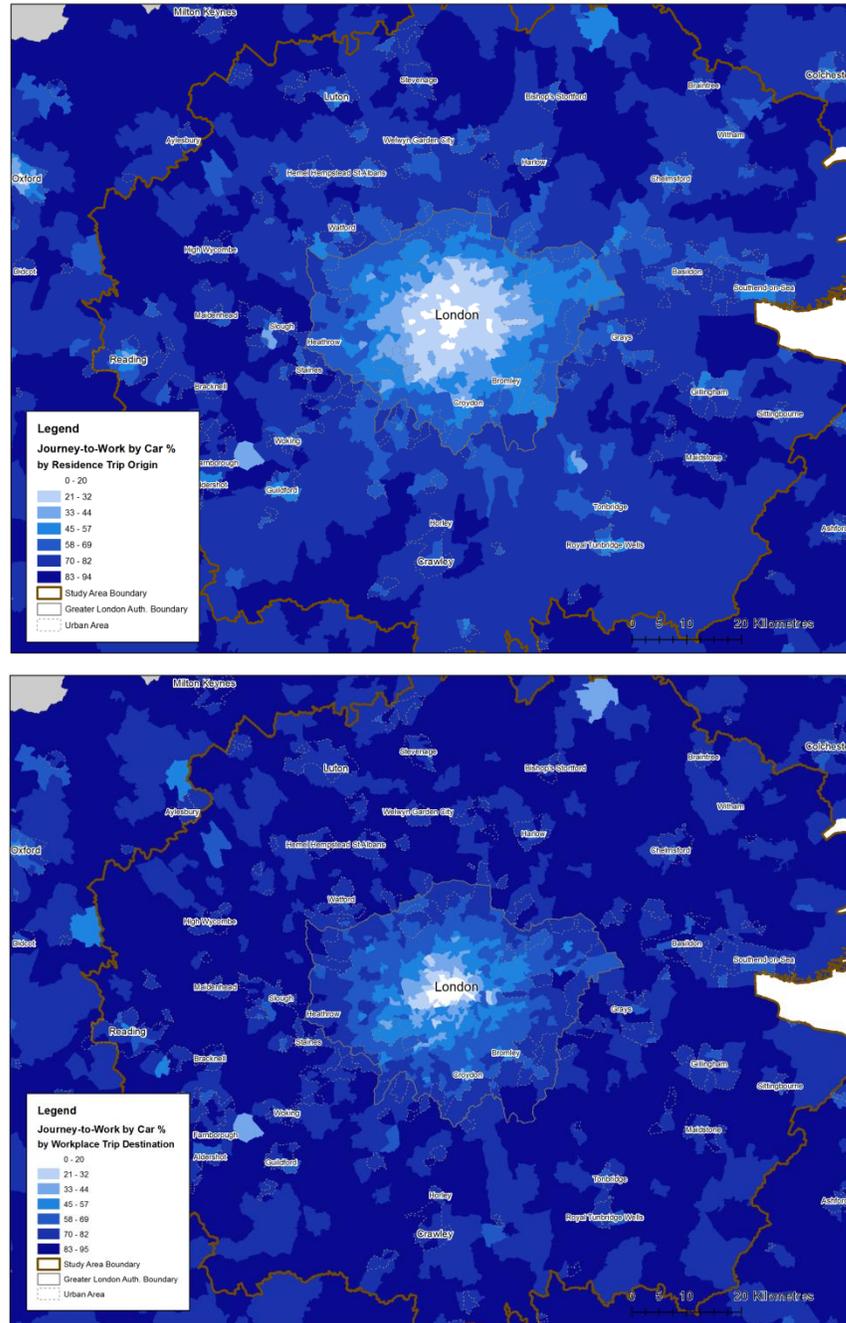
Figure 6.19 & 6.20: Car Journey-to-work by Trip Origin (above) and Trip Destination (below). Data Source: Census 2001 (ONS, 2010b).

Further to the overall sub-regional trends, Figure 6.18 highlights finer-scale intra-urban patterns related to the performance of specific employment centres. In Outer London, larger centres such as Croydon and Bromley to the south have relatively higher proportions of public transport travel above 30% compared to the rest of Outer London. In Inner London, Canary Wharf stands out as

achieving similarly high levels of public transport to Central London (more than 60%). Whilst public transport travel is low beyond Greater London, the pattern of larger centres featuring higher proportions of public transport continues, with Reading and Southend measuring around 20% of trips by public transport. Another trend that can be seen is a greater degree of car usage from residents in the Western Sector. This reflects the relatively lower flows from this region into Greater London, as identified in Section 6.2, with instead more trips to sub-regional job opportunities in the Western Sector by car.

The geographical patterns for walking and cycling journey-to-work proportions are less distinctive, as shown in Figures 6.21 and 6.22. Indeed there is a greater degree of clustering by trip origins rather than destinations, highlighting larger mixed-use centres where live-work relationships are possible and trip distances are sufficiently short for active travel. Note there are several anomalies of rural wards with unusually high active travel proportions (50% and above), due to the presence of facilities such as army barracks. Generally towns in the Wider Study Area beyond Greater London have relatively high proportions of active travel, whilst Outer London generally performs poorly, with only Croydon and Richmond achieving low levels of active travel. These trends in the Wider Study Area may reflect a lack of public transport services beyond the GLA boundary, forcing non-car users to walk or cycle. Another trend is the very low levels of active travel recorded from and to Canary Wharf, indicating an absence of live-work relationships. This issue is discussed more fully in Section 6.5.

In summary there are distinct patterns of mode-choice for trip-origin residential and trip-destination employment geographies. Both patterns generally display dramatically more sustainable mode-choices for trips to Greater London compared to the wider region in terms of greater public transport travel. Residential origin patterns are more dispersed with public transport trips beginning across the region, but overwhelmingly ending in Central and Inner London. This evidence supports the view of strong spatial relationships between accessibility and mode-choice, particularly through trip destination locations. The mode-choice evidence strongly contradicts arguments that decentralised

urban forms can achieve sustainable travel patterns, though there is evidence that larger centres in Outer London and the Wider Study Area produce modest public transport travel levels.
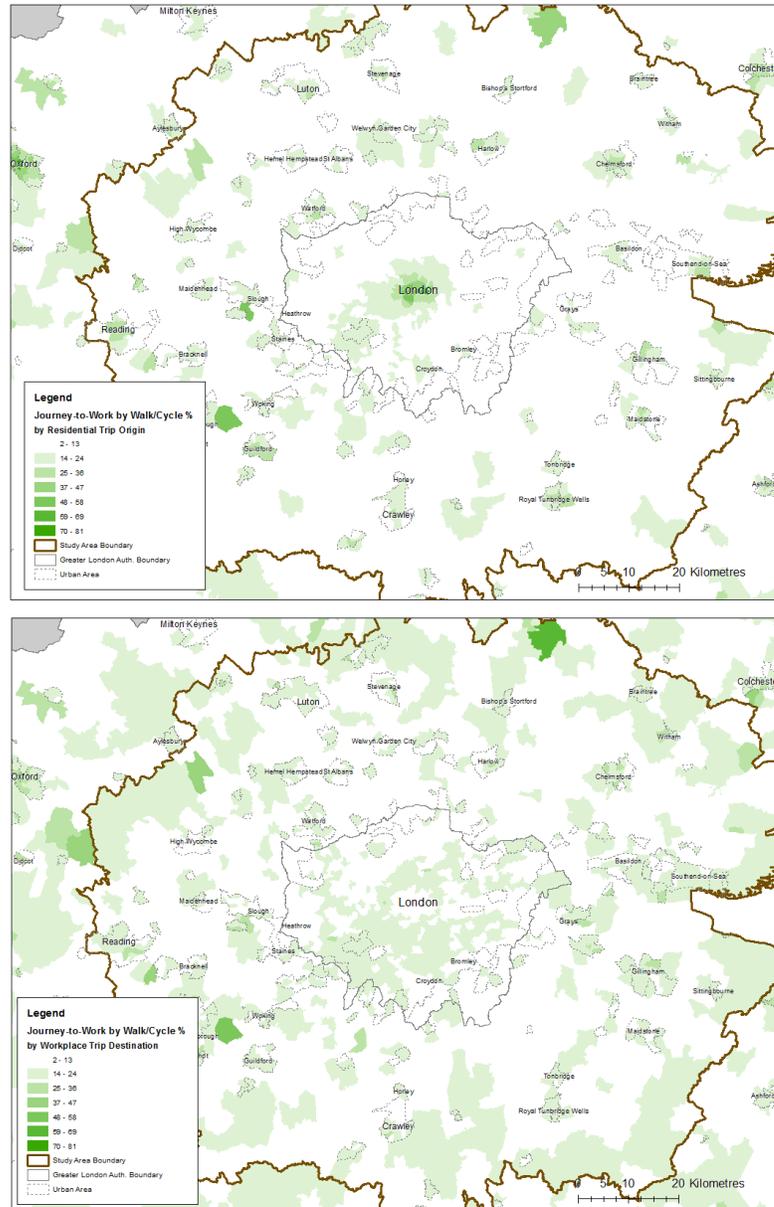
Figure 6.21 & 6.22: Pedestrian-Cycle Journey-to-work by Trip Origin (top) and Trip Destination (bottom). Data Source: Census 2001 (ONS, 2010b).

6.3.2   Mode-Choice Regression Analysis

Following the mapping analysis, we now test mode-choice relationships using multivariate regression models. Chapter 3 summarised the research evidence on

spatial relationships between urban form, socio-economic characteristics and travel behaviour, concluding that accessibility and socio-economic factors have the most significant statistical correlations with travel pattern variables, and that these are in turn correlated with built-environment variables. In this section we test these theoretical assumptions in trying to predict the core mode-choice variable of proportion of journey-to-work trips by car, with the addition of employment specialisation variables to test relationships between employment geography and travel patterns. Firstly we discuss the form of regression used and potential sources of error, then key univariate relationships in the study area are highlighted. Finally a multivariate regression analysis of accessibility, socio-economic, employment specialisation and built-environment variables is performed.

The multivariate regression analysis is intended to rank variables in terms of statistical significance and identify multi-collinearity relationships. Inferential analysis cannot prove causality, but it does provide statistical evidence on variable associations to back-up the connections identified in mapping and qualitative analysis. There are significant choices regarding the form of the regression used. The basic unit of regression can be zones, or can be interactions between zones. Interaction based modelling has the advantage of considering both origin and destination properties simultaneously, thus more realistically representing how individuals make travel decisions. It also provides a far greater sample size of around 200,000 ward interactions compared to 1,700 wards in the study area. The interaction approach supports the earlier stated goals of the meso-scale analysis (discussed in Chapter 3) in bridging between aggregate models and more detailed disaggregate individual-level transport models, as more disaggregate interaction-specific data can be introduced (e.g. occupational class and flow travel time). Note there are issues regarding which datasets are available disaggregated by flows, as discussed later in this sub-section. As travel flows vary by numbers of trips, weighted least squares regression is appropriate and is used throughout this chapter. The analysis uses linear regression which will lead to errors where non-linear relationships are present. Logarithmic forms of independent variables are tested to allow a degree

of non-linearity in relationships to be modelled. The full list of variables tested is given in Appendix G.

A particular issue with the variables used in this analysis in the presence of proportional or ratio variables. These proportional variables include the mode-choice dependent variable analysed in this section, and several of independent variables used throughout the regression analysis in this chapter. These include household composition and occupational class variables. These proportional variables are very common in aggregate analysis as we have many zones with varying populations and need to control for these varying populations. The use of proportional variables has however been criticised by statistical researchers as breaking regression assumptions and potentially leading to misleading results (Kronmal, 1993; Firebaugh and Gibbs, 1985). Proportional variables are commonly used in geographical and sustainable travel regression analysis, and this common practice is followed here, though the potential for introducing errors through this approach must be borne in mind.

We begin by identifying key univariate relationships before moving on to the multivariate regression analysis. The correlation between sustainable travel and high urban densities is a long running debate in urban travel research (see Chapter 3), and the relationships between activity density[1] and the proportion of journey-to-work trips by car is graphed in Figures 6.23 and 6.24. There is an inverse correlation, though this is notably stronger for the trip destination density graph than the trip origin density.

---

[1] Activity density is defined as total residents plus employees. Note that substituting activity density with residential or employment density significantly weakens the mode-choice correlations.
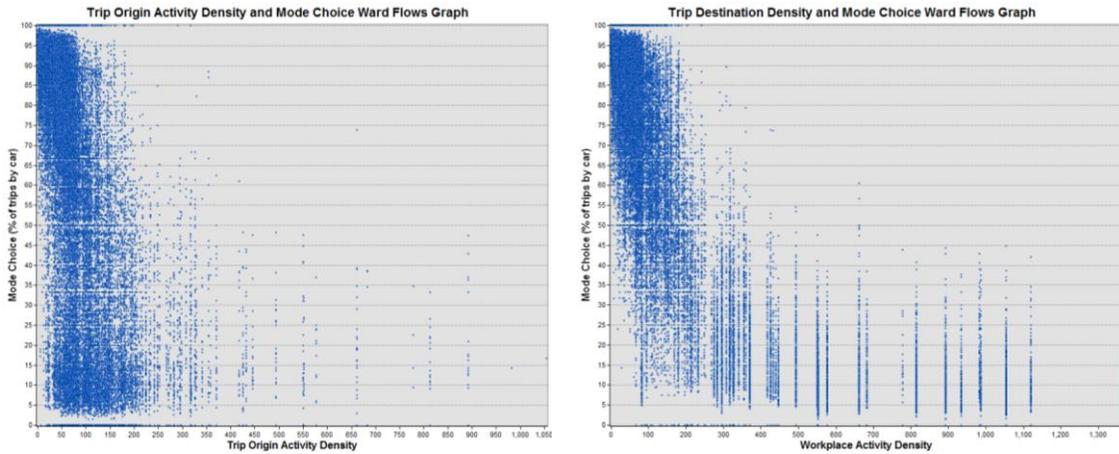
Figures 6.23 & 6.24: Graphs of Density and Mode-Choice for Ward-to-Ward Interactions by Trip Origin (left) and Trip Destination (right).

We argued in Chapter 3 that in terms of influencing travel behaviour, density is a proxy variable for accessibility and socio-economic factors. Processes of urban development and subsequently densities result from the accessibility and transportation connections of an area in the context of the wider city-region. Relationships between public transport accessibility using the Hansen Indices[1] from Section 6.1 and the aggregate proportion of car trips are shown in Figures 6.25 to 6.26. There are similar inverse correlations with density (indicating that accessibility and density are closely related) though the accessibility measures produce much more linear relationships than the density graphs. Again the trip destination factor produces a stronger relationship, and indeed this is the strongest univariate correlation of any variable, with an R^2 value of 0.81. The equivalent road accessibility variables showed much weaker correlations. It is likely that the public transport accessibility and urban density variables are negatively correlated with car ownership and parking cost, thus enhancing their inverse correlations with car travel. The trend of destination factors producing

---

[1] The accessibility measures can be tuned by varying the distance decay parameter x. Higher values of x intensify local variation and produce curves resembling the density graphs. The graphs use population as the opportunity measure, whilst substituting this for employment produces less linear relationships due to the clustered nature of jobs.

stronger correlations provides further evidence for the argument made in the sub-regional discussion in Section 6.2, where high density-accessibility destinations simultaneously encourage public transport travel and minimise car travel, whereas these effects are significantly less marked from the perspective of trip origins.
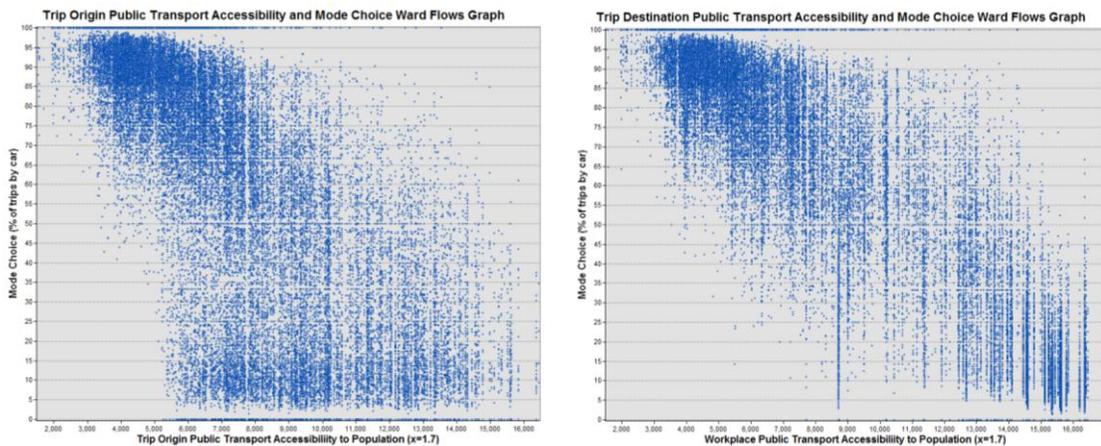
Figures 6.25 & 6.26: Graphs of Accessibility and Mode-Choice for Ward-to-Ward Interactions by Trip Origin (left) and Trip Destination (right).

In addition to the accessibility indices shown above, we can also measure travel costs specific to individual travel flows. When travellers make mode-choice decisions they weigh-up travel options in terms of cost, thus relative measures of travel cost between modes should be good predictors of mode-choice. Relative accessibility between car and public transport is mapped in Figure 6.27, displaying a clear 'S' shaped logarithmic relationship. While there is considerable scatter in the distribution, it can be seen that for trips where public transport is twice as slow or more as a car journey, car trips dominate. Conversely where public transport is faster than car travel, then the proportion of car travel is minimal. The correlation of the log of relative accessibility produces an R^2 value of .56.
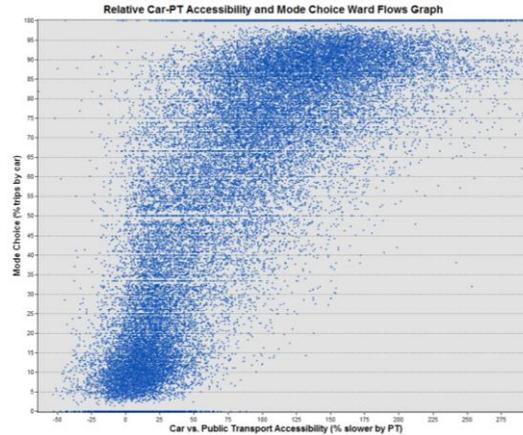
Figure 6.27: Relative Car-PT Accessibility and Mode-Choice for Ward Flows.

In addition to accessibility and density, there are also important relationships with socio-economic variables. The occupational class employment specialisation variables failed to produce a significant univariate relationship with car travel (though they were significant in the multivariate regression analysis) indicating they are not amongst the most influential factors in mode-choice. The strongest socio-economic correlation is with car ownership, as shown in Figure 6.28, which produces an R^2 value of 0.79 at an aggregate ward scale (car ownership data is not available disaggregated by ward interactions). Clearly at this scale there is a high probability for car owning households to use their cars in journey-to-work trips. It is also instructive to map the residuals in this relationship as shown in Figure 6.29. The blue wards have lower proportions of car use than the correlation predicts given their level of car ownership. These wards are overwhelmingly located within or adjacent to Greater London, reflecting the minimisation of car use here through restricted parking and relatively good public transport. It is also apparent that these areas include the wealthiest residential districts in Greater London. It appears that households in these locations can afford to own 'optional' cars that are not used for work travel. Other socio-economic variables tested against mode-choice included household size and estimated income. Estimated income failed to produce strong univariate relationships. Household structure variables produced moderate univariate relationships, with the best goodness-of-fit being the

275

inverse relationship between proportion of single households (prominent in
Inner London) and car use.
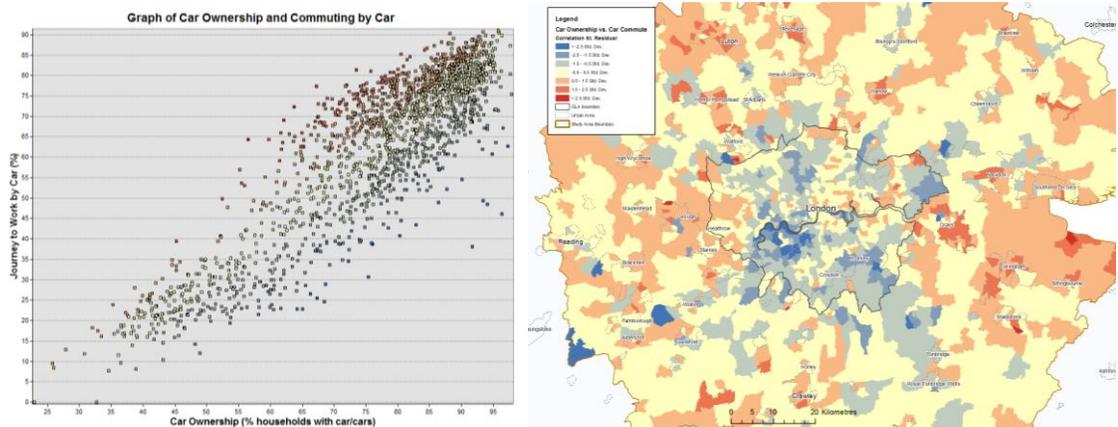
Figure 6.28 & 6.29: Car Ownership and Mode-Choice Relationships, Graph (left) and
Standardised Residuals Map (right).

We now move to the multivariate regression analysis to rank these many factors
in terms of statistical influence. A stepwise multivariate linear regression
method was used with the independent variables described above (including
those that failed to produce strong univariate correlations) to predict the
aggregate proportion of journey-to-work trips by car. The full list of
independent variables is provided in Appendix G, along with the full tables for
all the regression models in this Chapter. A major issue with the application of
multivariate regression models in an urban geography context is multi-
collinearity, which can break the assumption of variable independence and lead
to misleading coefficient values. Variables that display very high levels of
multi-collinearity[1] were removed from the analysis, whilst those variables with
moderately high collinearity values are indicated in the tables. This process
generally leads to those factors tested using multiple variables (e.g.

---

[1] Multi-collinearity was assessed using the common Variance Inflation Factor (VIF) measure. A VIF
greater than 10 is taken to indicate very high multi-collinearity, and a VIF between 5 and 10 is taken to
indicate moderately high multi-collinearity (Menard, 1995). The full VIF results are provided in Appendix
G.

accessibility) being represented by a single variable in the final models, with only the most significant variable identified in the stepwise regression being included.

The results are shown in Table 6.2, with the high R^2 values showing a strong goodness-of-fit for these models. Note there are three models to test the effect of significant independent variables being excluded. In Model 1 car ownership is strongly correlated with increased car travel, being the second most influential variable. Note that car ownership and income data is not available disaggregated by flows, and subsequently their influence may be underestimated in the models. Model 1 has multi-collinearity issues, with car ownership linked to the accessibility variables. It is useful to remove car ownership to see if it can be predicted from the remaining independent variables, and test if this resolves the multi-collinearity problems. Car ownership variables are removed in Model 2, and the similarly high R^2 value shows that car ownership can be predicted from the remaining variables, in particular the accessibility and single household variables. Additionally the multi-collinearity problems are no longer present. Model 3 tests the relationship without the flow specific travel cost variables, and again the results show that this variable can largely be predicted from the remaining variables.

The main results of the regression models are that accessibility is the dominant factor, and is strongly related to lower car use. High accessibility is also related to low car ownership as is the single households variable (associated with urban areas) whilst high residential income is connected to high car ownership. It is the destination accessibility variable in particular that is the most significant in all the models, backing up the conclusions from the earlier univariate analysis that destination accessibility is more significant than residential accessibility in predicting mode-choice. The relative accessibility variable (measuring how much faster car travel is than public transport) is also ranked very highly in Models 1 and 2, though can be largely be predicted from the other variables as shown in Model 3. The density variables are not significant in these models, confirming the argument from Chapter 3 that built-environment variables are only correlated through their relationship with accessibility.

Table 6.2: Ward Interaction Car Mode-Choice Models: Goodness-of-Fit and Ranked Coefficients

	1. Car Trips % by Flow (including car ownership variables)	**2. Car Trips % by Flow** (excluding car ownership variables)	**3. Car Trips % by Flow** (excluding flow distance and car ownership variables)
	Regression weighted by flow trip volume	Regression weighted by flow trip volume	Regression weighted by flow trip volume
	R = .924	R = .918	R = .892
	Adjusted R² = .854	Adjusted R² = .842	Adjusted R² = .796

Dependent Variable & Goodness of Fit (left margin label)

Coefficients Ranked by Standardised Beta (left margin label)

Coefficient Name	St. β	Coefficient Name	St. β	Coefficient Name	St. β
Workplace Accessibility to Employment (PT, x=1.7, log)	-.455*	Workplace Accessibility to Employment (PT, x=1.7, log)	-.472	Workplace Accessibility to Employment (PT, x=1.7, log)	-.676
Car Ownership (households with 1+ car %)	.367*	Flow Relative Car to PT Time (mins faster by car)	.310	Residence Single Households (%)	-.169
Flow Relative Car to PT Time (mins faster by car)	.301	Workplace Commercial Rental Value (VOA estimate)	-.131	Workplace Commercial Rental Value (VOA estimate)	-.107
Residence Accessibility to Population (PT, x=1.7)	.236*	Residence Single Households (%)	-.103	Residence Household Income (ONS estimate)	.058
Workplace Commercial Rental Value (VOA estimate)	-.138	Workplace Employment Special. 2 (Professional %)	-.059	Workplace Employment Special. 2 (Professional %)	-.049
Residence Household Income (ONS estimate)	-.090	Residence Household Income (ONS estimate)	.052		
Workplace Employment Special. 2 (Professional %)	-.071				
Workplace Employment Special. 1 (Management %)	.016				

Coefficients significant to 0.99.

***Coefficient has tolerance between 0.1-0.2 and/or VIF between 5-10 indicating collinearity (note high collinearity variables with tolerance < 0.1 and/or VIF > 10 removed according to procedure described on page 229) .

The employment specialisation variables have only modest relationships with car mode-choice. The professional category (the top three occupational classes) is associated with reduced car use likely through the connection to London based jobs. Additionally workplace commercial rental value is linked to lower car use. Both of these variables relate to high density specialised centres, typically with limited car parking. Further relationships between occupational class and public transport choices were identified by Titheridge and Hall (2006), such as more affluent occupational classes favouring rail over bus modes. In this research the main relationships identified with employment specialisation variables are with travel distances, as discussed in the next section.

6.3.3   Summary

The mode-choice analysis has provided evidence for the two main themes of this chapter: assessing the travel sustainability for the London region at intra-urban scales, and exploring the underlying drivers of travel patterns. Regarding the London travel sustainability measures, journey-to-work mode-choice behaviour is overwhelmingly less sustainable in the wider region beyond Greater London (and to a degree outside of Inner London), particularly when analysed from trip destination perspectives. The significance of trip destinations relates directly to the importance of employment geography, with the poor performance of employment centres beyond Inner London highlighting the key issue of employment decentralisation leading to car dependent mode-choice patterns. The one caveat is that larger towns in Outer London and the wider region perform marginally better in public transport terms. This scale effect (related to increased public transport system feasibility and car travel costs in larger settlements) may be more marked in a study region with larger sub-cities, rather than the network of relatively small towns that is present in the London region.

In regard to the second aim of testing the theory of travel behaviour and urban form, the overall conclusion is that there is a close correspondence between the theoretical argument from Chapter 3- that accessibility and socio-economic factors determine travel patterns- and the mode-choice regression results. In fact the results point to an even stronger role for accessibility than anticipated, with public transport accessibility indices being the most highly ranked factor in all of the three regression models. Again the results clearly show that destination accessibility is the more significant in influencing mode-choice than residential origin factors. The clear importance of trip destination factors supports the intra-metropolitan basis of this research- as this approach can consider trip origins and destination simultaneously- and undermines any narrowly focussed residential-based trip analysis that excludes the regional context. In addition to accessibility, car ownership was strongly correlated with high car use, and is connected to accessibility and household composition variables. The employment specialisation variables are moderately correlated with lower car

travel, likely due to their connection with Inner London, and were not found to play a major role in mode-choice.

6.4 Journey-to-Work Travel Distance Analysis

Alongside mode-choice, the most significant determinant of travel energy use, and carbon emissions, is travel distance (see Chapter 3). Whilst mode-choice decisions can be modelled in terms of the specific journey accessibility characteristics, trip distance behaviour is somewhat more abstract and relates to residential location and labour market patterns. Residential location and labour market processes do however have relationships with the same accessibility, socio-economic and built-environment variables considered in the mode-choice analysis. The employment geography focus of this research allows an intra-urban economic perspective on trip-distance patterns, particularly including employment specialisation variables.

6.4.1 Average Journey Distance by Trip Origin and Destination

Using the routing analysis from the accessibility model we can estimate journey distances according to the origin, destination and mode-choice data from the 2001 Census. The mean journey-to-work distance by residence map is shown in Figure 6.30. There is a clear urban-rural divide, with longer average distance commuting from more remote locations contrasting with shorter distance travel in urban locations. Average distances are lowest in Central and Inner London. In addition to the urban-rural pattern there is a pronounced east-west division, with shorter distances in the western half of the wider region, particularly in larger towns such as Reading and Luton, and longer distances in the east in towns such as Southend and Chelmsford. This indicates that the uneven employment geography of the region (discussed in Chapter 5) is influencing travel distances, with poorer employment accessibility to the east leading to longer distance commuting in this sub-region.
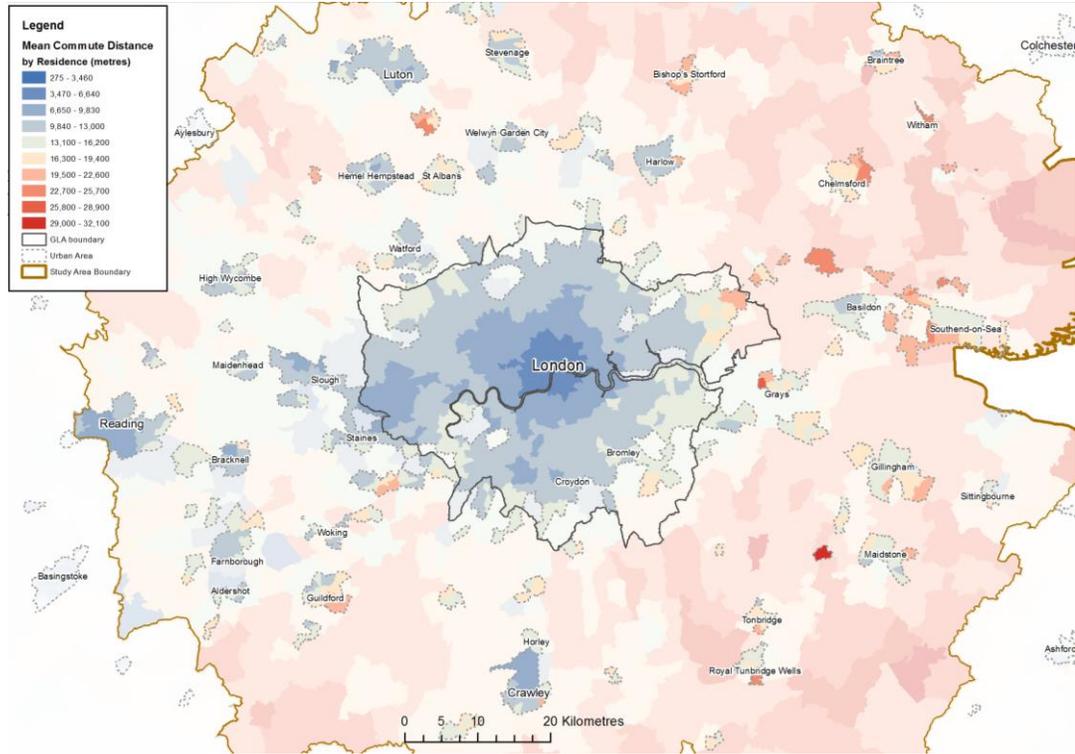
Figure 6.30: Mean Journey-to-Work Distance by Residential Trip Origin.
Data Source: Census 2001 (ONS, 2010b).
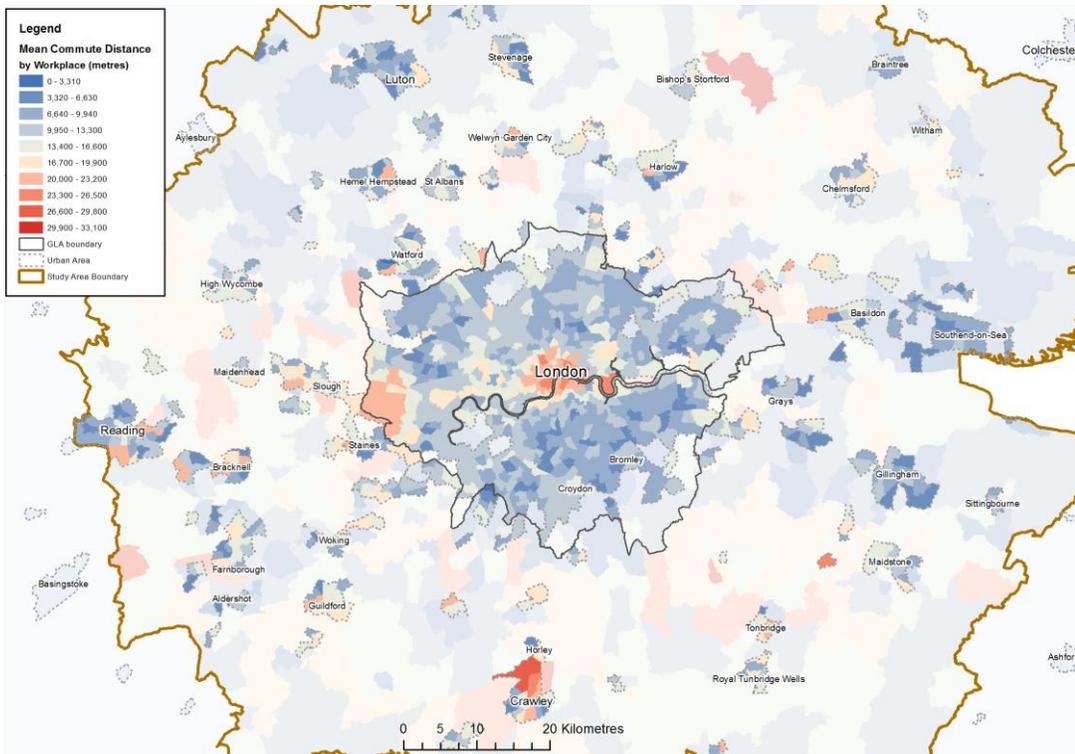
Figure 6.31: Mean Journey-to-Work Distance by Workplace Trip Destination.
Data Source: Census 2001 (ONS, 2010b).

The mean distance map by employment destination provides a dramatically different pattern to the residential origin map, as shown in Figure 6.31. There is intensive variation identifiable between employment centres, revealing that significant travel pattern clustering is occurring at intra-urban scales. Trips connected to Central London are very long distance, as are those to Canary Wharf. Note these long distance trips are narrowly confined to the Central Activities Zone whilst the majority of Inner and Outer London has surprisingly short distance trips. Longer distance trip patterns are also found in and around Heathrow and in a number of locations in the Western Sector, such as Bracknell and Slough. There appears to be a strong connection between long distance travel and the specialised employment centres identified in the Chapter 5 analysis. This relationship is analysed statistically in the next section. Additionally airport locations stand out as long distance travel destinations, particularly the larger airports of Gatwick (north Crawley) and Heathrow. This issue is returned to in Section 6.5.

Overall the map analysis indicates that journey-to-work distances result from interactions between employment accessibility and employment specialisation. The most successful employment areas, with high concentrations of specialised jobs, tend to have long distance trips for employees, attracted to the high skill jobs, and short distance trips for the low number of residents, who benefit from the high numbers of job opportunities nearby. Conversely areas with low employment accessibility force residents to travel further for work due to a shortage of jobs, whilst the small numbers of jobs that are available are met by local residents. We can integrate these varied residential and workplace patterns into a single map by calculating a mean trip length of both residential and workplace trips. This is equivalent to a weighted average reflecting the balance of residents to jobs. The resulting map is shown in Figure 6.32. The rural-urban divide remains strongly apparent. The shortest distance trips are found in Inner London and some large towns such as Reading and Luton. Central London and Canary Wharf are special cases with very long distance travel attracted to highly specialised business agglomerations. Other long distance areas include large airports and a small number of isolated towns in the wider region. The east-west

divisions in the wider region identified in Figures 6.30 and 6.31 have generally balanced themselves out with moderate distance trips in both areas.
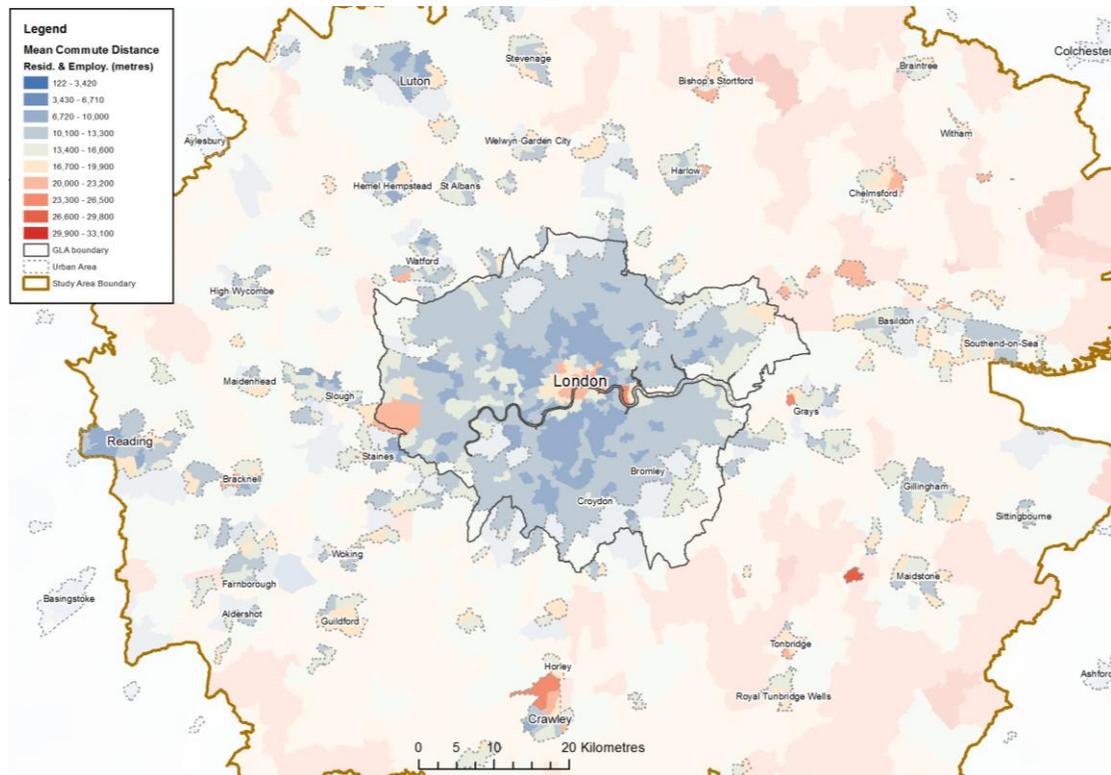
Figure 6.32: Weighted Mean Journey-to-Work Distance by Residential Origins and Workplace Destinations. Data Source: Census 2001 (ONS, 2010b).

6.4.2   Journey-to-Work Distance Regression Models

Similar to the previous mode-choice regression modelling, here we analyse travel distance patterns statistically, firstly considering general univariate relationships, and secondly using multivariate models. There are some differences in the categories of independent variables included in the distance analysis compared to the mode-choice analysis. Essentially we are interested in understanding the residential and employment location properties that underpin travel distance patterns. As residential and employment location decisions are generally made by individuals in advance of specific journey decisions such as mode-choice (in the same way that Trip Distribution comes before Mode-Choice in the classic four stage model discussed in Chapter 2) it makes sense to exclude mode-choice variables from the analysis of distance, as this would pre-empt the location decisions we are trying to understand. Furthermore variables

directly connected to the specific journey-to-work trip (e.g. trip time) are similarly not appropriate independent variables.

At the residential origin of journey-to-work trips we would expect a close relationship between accessibility indices and average journey-to-work distances. This is indeed the case, and the strongest correlation is with the public transport accessibility index. This produces an R^2 value of .575 and is shown graphically in Figure 6.33. The sub-region classification in Figure 6.39 illustrates how the accessibility-distance relationship is based on the urban-rural division identified earlier in Figure 6.30.
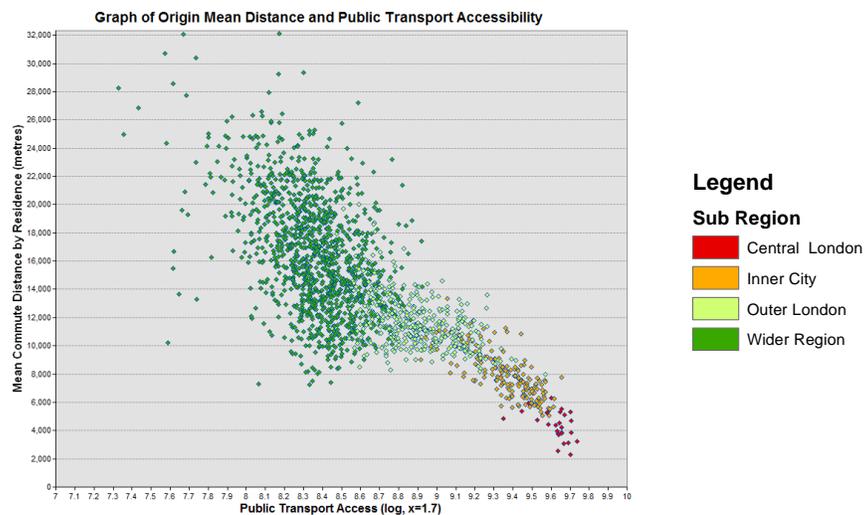
Figure 6.33: Graph of Origin Employment Accessibility and Journey-to-Work Distance.

Explaining journey-to-work distances by trip destinations is less straightforward than by trip origins, as there is no such simple relationship with accessibility. By graphing employment accessibility with destination journey-to-work distances we can see a regional jobs-housing balance relationship as shown in Figure 6.34. The more peripheral wards in the wider region include many high mean-distance wards (although this sub-region is the least coherent in terms of travel distances). Average trip lengths fall substantially for destinations in Outer London and most Inner London wards as these areas find the best balance between employment accessibility and residential location. Finally the highest accessibility Central London wards (along with some Inner London wards) display a dramatically contrasting trend with the longest mean-distances in the

study region. These relationships produce the loosely bimodal distribution that was identified earlier in Figure 6.38 mapping analysis.
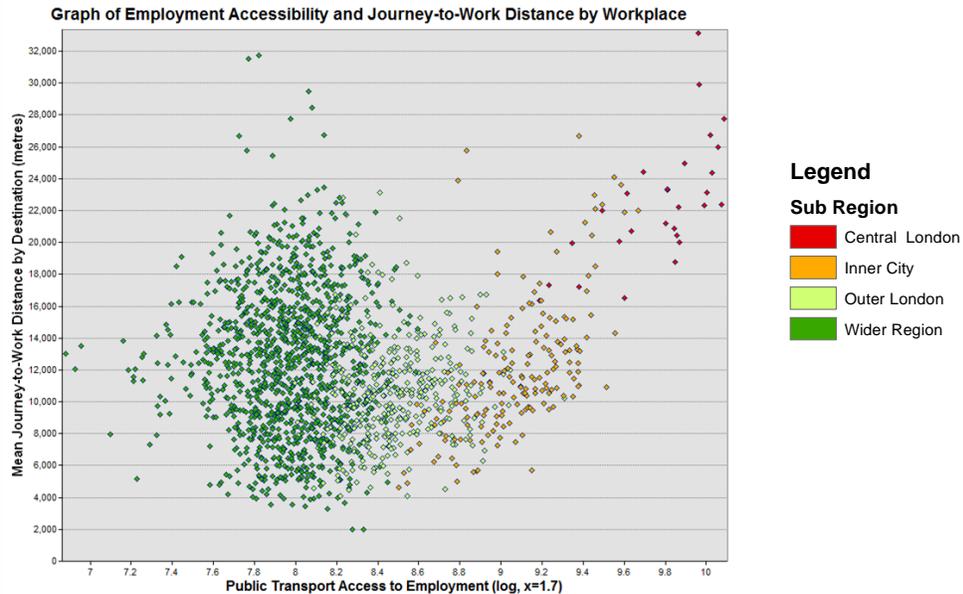
Figure 6.34: Graph of Destination Employment Accessibility and Journey-to-Work Distance.

This result prompts the important question of what factors are causing the long distance travel patterns to Central London. This research proposes employment specialisation as the driving force of these long distance patterns. There are several mechanisms by which employment specialisation can influence travel distance. From the perspective of firms, specialised jobs require scare skills and consequently are likely to draw on labour markets from further afield to meet these skills. At an employee level, specialised jobs will generally pay higher wages, which can in turn fund more expensive long-distance commuting by rail and car, and also allow greater freedom in the housing market. Lastly considering the link between employment specialisation and high commercial rents (discussed earlier in Chapter 5) it is clear that specialised jobs are clustered spatially through agglomeration processes, and these processes drive up rents in areas of high employment which in turn limits local housing opportunities.

The employment specialisation indicator of management employment discussed in Chapter 5 is linked to travel distance as shown in Figure 6.35. This has the

strongest univariate relationship against destination mean-distance of all the variables tested. Note however the correlation is only moderate at an R² of .311, and there is much variation left unexplained. The map in Figure 6.36 shows the spatial pattern of regression residuals. It appears that the main business activity areas, such as Central London and Canary Wharf, are under-predicted, likely because of a non-linear aspect to the specialisation relationship. Furthermore there are significant under-predictions for airports and industrial parks, implying that there are further forms of specialised employment (e.g. related to specialised infrastructure facilities) that the management proportion indicator does not identify. Whilst there are several alternative measures we can use to examine employment specialisation, such as measures of jobs-housing balance, these variables were not found to improve on the univariate relationships with management employment shown in Figure 6.36. Commercial rent was found to be significant in the multivariate models described below. There is scope for future research to develop further specialisation indicators, perhaps linking specific sectors, such as manufacturing, to travel distances.
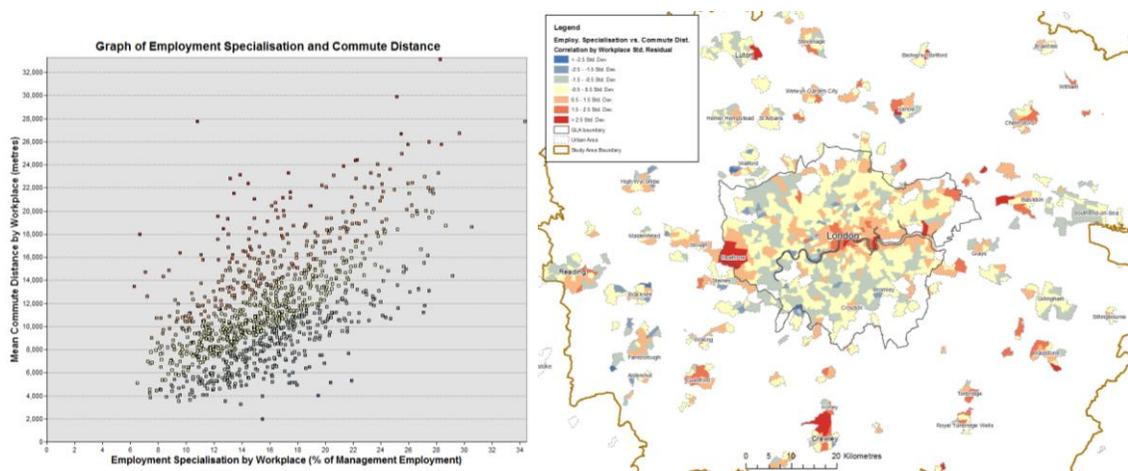
Figure 6.35 & 6.36: Relationships Between Employment Specialisation and Journey-to-Work Distance, Graph (left) and Standardised Residuals Map (right).

We now move the discussion to the multivariate regression model. The interaction-based model has the advantage that certain variables, such as socio-economic characteristics, can be measured as disaggregate flow variables, measuring the properties of individuals travelling between particular residence and workplace zones. While data disaggregated to flows is more limited in the

286

UK census, employment class data is available by journey-to-work flow, allowing the calculation of interaction-based employment specialisation measures. Basic household structure data distinguishing between single households and couple households are also available disaggregated by flow. As discussed previously the interaction data does not include income or car ownership variables disaggregated to flows, and this is consequently a limitation of the model. The goodness-of-fit and standardised coefficients for the interaction-distance model are shown in Table 6.3.

Table 6.3: Ward Interaction Distance Model (Car Ownership and Mode-Choice Variables Excluded): Goodness-of-Fit and Ranked Coefficients

Dependent Variable & Goodness of Fit	
4. Flow Distance (network distance, weighted mean of modes used)	
Regression weighted by flow trip volume	
R = .752	
Adjusted R² = .566	

Coefficient Name	St. β
Workplace Accessibility to Employment (PT, x=1.7, log)	.861
Residence Accessibility to Population (PT, x=1.7)	-.717
Flow Employment Special. 2 (Professional %)	.164
Workplace Airport Function (% air trans)	.121
Residence Household Income (ONS estimate)	-.119
Residence Activity Density (log)	-.114
Workplace Commercial Rental Value (VOA estimate)	.095
Flow Couple Household %	.095
Flow Employment Special. 1 (Management %)	.089
Workplace Activity Density (log)	-.077

Coefficients significant to 0.99.

In Model 4 we have two accessibility variables being offset against each other, with origin based access to population reducing trip distances, and destination access to employment increasing trip distances. The destination employment accessibility measure is connected to the increased distances associated with specialised locations such as Central London. The importance of specialisation

in increasing trip distances is further emphasised by the flow-based employment specialisation variables, particularly the professional employment variable which was found to have the third highest standardised beta value. These variables are linked to higher income employees in more specialised labour markets. In addition to specialisation being a property of employees, it is also a characteristic of places, as emphasised by the importance of the commercial rent variable in increasing trip distances, along with the main workplace employment accessibility variable. As the employment specialisation variables used here are unable to account for long distance travel to airports, a variable representing airport employment functions has been introduced in this model. This variable has a surprisingly high standardised beta value, likely due to the large numbers of employees in airport facilities in the London region.

Aside from accessibility and specialisation, other important variables include the flow-based couple household variable, which increases distances and is connected to workers making more distant residential location choices through two-worker household and dependent children influences. The residence household income variable produced an unexpected negative correlation with travel distance. This is likely related to Greater London housing markets being so expensive that it is very difficult for less affluent groups to afford to live close to Greater London workplaces. Another factor is employment specialisation variables having positive relationships with income, and the aggregate residential income variable offsetting these. A more detailed disaggregate income variable is needed to get a more complete picture of the influence of income and its relationships with employment specialisation.

6.4.3   Summary

While the analysis of journey-to-work distances proves to be less straightforward than mode-choice, important relationships have been demonstrated in this analysis. Travel distances show intensive intra-metropolitan scale variation between employment centres, confirming the value of finer-scale regional approach taken in this research. The overall pattern is that high accessibility at trip origins reduces travel distances, whilst being offset by the increased distances to specialised employment centres such as Central

London and the Western Sector. The relationship between employment specialisation and travel patterns has been given little attention in the sustainable travel literature, and in this analysis the specialisation variables are strongly correlated with longer distance travel, second only to accessibility variables in predicting trip distances. The results are indicative of tensions between the sustainability goal of minimising travel distances and the regional specialised labour markets that underlie world cities such as London. We hypothesised that connections between employment specialisation and travel patterns could be both at the disaggregate level of employees, acting through job markets and income, and at the more aggregate level of agglomerations, acting through overheating property markets. Both these processes can be identified in the final flow-based regression model, with flow-specific occupational class specialisation variables correlated with longer travel distances, and the commercial rent variable correlation indicating that high value workplace property markets are also connected to long distance travel. Thus specialisation is a multi-faceted phenomenon cutting across firm location, residential location and property market processes.

6.5 CO_2 *Emissions Indicator Analysis*

The previous sections in this chapter have analysed mode-choice and distance patterns for journey-to-work trips, highlighting various accessibility, socio-economic and employment specialisation relationships. Here we combine both the mode-choice and distance data in an integrated travel sustainability indicator of journey-to-work CO_2 emissions. This allows the overall travel sustainability patterns across the region and the performance of individual urban sub-centres to be quantified and profiled using the headline indicator of CO_2 emissions.

6.5.1   Journey-to-Work Sustainability: Carbon Dioxide Emissions Analysis

The CO_2 emissions indicator uses interactions between wards as the basic unit, and is derived from the mode-choice and distance interaction data described in the previous sections. There are three basic stages in the calculation of the indicator: firstly the journey-to-work trips between wards are compiled by mode

(Section 6.3); secondly these are combined with the mode-specific distances for each flow (Section 6.4); and finally these flow distances by mode are multiplied by CO_2 emissions per-kilometre coefficients, in this case supplied by the UK government and Transport for London. These coefficients are detailed in the earlier methodology chapter in Sub-Section 4.7.3. The indicator can be calculated as a total emissions measure or as a per-capita measure, with each providing complementary insights into journey-to-work sustainability patterns. Sub-regional emission totals are provided in Table 6.4, with the sub-regional per-capita emissions listed in Table 6.5. The results include external trips from residents in the Greater South East Region (shown in the origin sub-regions in Table 6.4 and 6.5) but do not include trips originating beyond this. These excluded long-distance commuting trips account for 1.8% of the journeys to the study area.

The destination totals at the bottom of Table 6.4 show that jobs in Central and Inner London together account for 25% of emissions, Outer London jobs account for another 24% of emissions, with the remaining 51% of emissions resulting from trips to jobs in the Wider Study Area. Thus half of all emissions are occurring to jobs in the wider region, strongly emphasising the necessity of a regional perspective in any comprehensive travel sustainability analysis. The origin totals also show half of the emissions resulting from the Wider Study Area. The highest emission trip types generally involve interactions across the GLA boundary, particularly trips from the Wider Study Area to Outer London (10.3% of total emissions) or the reverse commuting case from Outer London to the Wider Study Area (7.5% of total emissions). These trips are often orbital in character, thus favouring car journeys. These conclusions are backed up by the per-capita emissions figures in Table 6.5, with flows across the GLA boundary, particularly those originating in the Greater South East, showing very high per-capita emissions. By far the biggest sub-regional emissions total is from trips beginning and ending in the Wider Region, accounting for 30.2% of emissions. Yet in per-capita terms we can see in Table 6.5 that trips beginning and ending in the Wider Region have per-capita emissions of 1.9 $kgCO_2$, which is only marginally higher than the regional average of 1.84 $kgCO_2$. Flows across the GLA boundary have high emissions in per-capita terms as well as in absolute

terms. Within Greater London, the highest emission flows involve interactions
between Outer London and Inner London, and flows within Outer London.
These types of trips tend to be orbital and do not favour public transport travel.

Table 6.4: Total Journey-to-Work CO_2 Emissions by Origin and Destination Sub-Region
(units: kg CO_2; one-way AM peak trip only)

Destination Sub-Region

		Central London		Inner London		Outer London		Wider Study Area		Origin Sub-Region Totals	
		Total kgCO₂	%	Total kgCO₂	%	Total kgCO₂	%	Total kgCO₂	%	Total kgCO₂	%
Origin Sub-Region	Central Ldn.	8,768	0.07	10,348	0.08	8,909	0.07	9,838	0.07	37,863	0.28
	Inner Ldn.	212,825	1.60	195,402	1.47	173,039	1.30	147,772	1.11	729,039	5.49
	Outer Ldn.	557,224	4.19	530,468	3.99	1,137,026	8.56	780,514	5.87	3,005,232	22.62
	Wider Study Area	724,130	5.45	491,109	3.70	1,374,486	10.34	4,012,557	30.20	6,602,281	49.69
	Greater South East	373,338	2.81	229,247	1.73	511,269	3.85	1,799,237	13.54	2,913,091	21.92
	Destination Sub-Region Totals	1,876,285	14.10	1,456,573	10.96	3,204,729	24.12	6,749,919	50.80	**Regional Total:** 13,287,506 kgCO₂	

Table 6.5: Per-Capita Journey-to-Work CO_2 Emissions by Origin and Destination Sub-Region
(units: kg CO_2; one-way AM peak trip only; standard deviations based on flows)

Destination Sub-Region

		Central London		Inner London		Outer London		Wider Study Area		Origin Sub-Region Totals	
		Per Capita kgCO₂	St. Dev.	Per Capita kgCO₂	St. Dev.	Per Capita kgCO₂	St. Dev.	Per Capita kgCO₂	St. Dev.	Per Capita kgCO₂	St. Dev.
Origin Sub-Region	Central Ldn.	0.162	0.23	0.513	0.50	1.737	1.39	5.385	3.88	0.467	2.24
	Inner Ldn.	0.618	0.33	0.483	0.71	1.676	1.60	6.256	4.12	0.832	2.61
	Outer Ldn.	1.379	0.80	1.705	1.47	0.991	2.35	4.860	4.38	1.485	3.25
	Wider Study Area	3.562	2.39	5.329	4.01	5.293	4.44	1.907	4.67	2.483	4.45
	Greater South East	7.748	6.08	11.131	8.87	17.179	9.44	9.130	8.63	9.855	7.84
	Destination Sub-Region Totals	1.494	4.01	1.483	4.37	1.777	5.71	2.162	6.17	**Regional Per Capita:** 1.84 kgCO₂	

A feature of the per-capita results in Table 6.5 is that there are high standard
deviations for a wide range of sub-regional flows. This indicates that there is
much variation at scales below the sub-regional level, and we can explore these

through mapping analysis. Total CO_2 emissions are mapped in Figure 6.37 for combined workplaces and residents. The results are largely a reflection of employment density, with high emission wards focussing on Central London and Canary Wharf (note that the major airports of Heathrow and Gatwick are also very prominent, and we return to this issue later in the discussion). Due to the highly uneven nature of urban densities across the study area, it is more insightful to focus the mapping analysis on per-capita rather than total emissions basis as this provides a means of comparing intra-urban centres of uneven size on an equivalent basis.
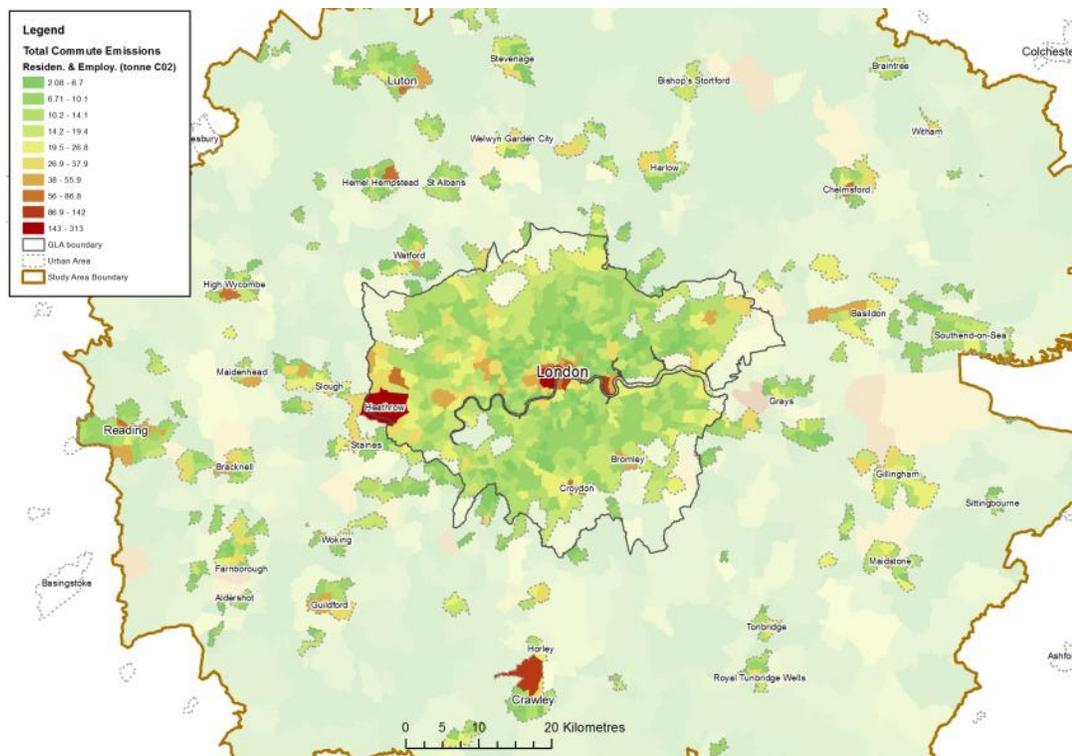
Figure 6.37: Total Journey-to-Work CO_2 Emissions, Combined Residents & Employees, 2001.

Per-capita emissions are mapped by residence in Figure 6.38. This produces a clear rural-urban split, with emissions much lower in urban areas, particularly in Inner London and the larger towns in the wider region such as Reading and Luton. These patterns match the previous mode-choice and travel distance analysis earlier in this chapter, including the longer distance travel from residents to the east of the wider region. This result confirms the research
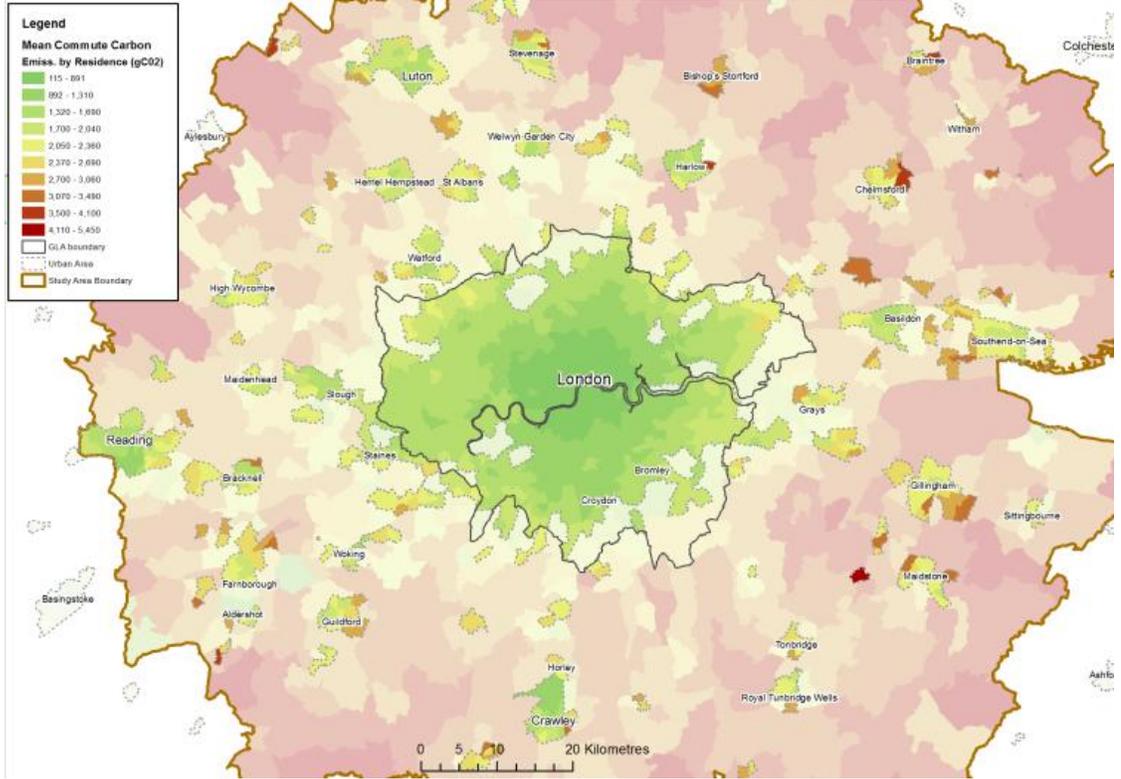
Figure 6.38: Mean Journey-to-Work CO_2 Emissions by Residence 2001.
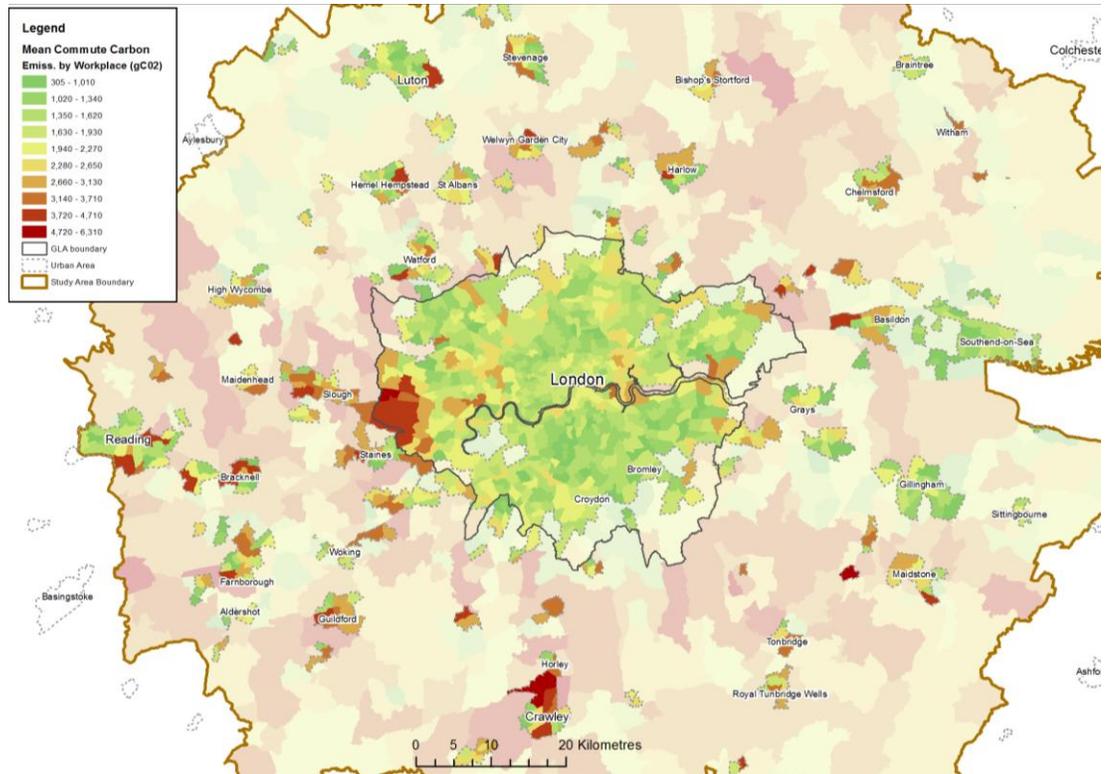
Figure 6.39: Mean Journey-to-Work CO_2 Emissions by Workplace 2001.

evidence detailed in Chapter 3 (Section 3.3) where studies identified relationships between increasing urban settlement size and more sustainable travel patterns.

When we switch the spatial referencing to workplaces, a highly contrasting picture emerges as shown in Figure 6.39. Much greater fine-scale heterogeneity between urban centres is evident. The Western Sector stands out as an area of higher emissions in towns such as Slough, Bracknell and in the cluster of business parks around Heathrow Airport. Industrially orientated centres in other parts of the region, such as Maidstone and Basildon, also have higher emissions. The major airports of Heathrow and Gatwick (and to a lesser extent the smaller airports of Luton and Stansted) have extremely high total and per-capita emissions from workforce travel. This likely reflects a series of factors including the very large size of airport workforces (attracting labour from longer distances), a lack of local housing, limited public transport access, good car parking availability and shift-working patterns outside of standard public transport hours. Given that air travel in general has extensive environmental impacts, this finding of major journey-to-work inefficiencies to airports is a further concern.

The residential and the workplace emission indicators are combined in Figure 6.40. This further confirms the urban-rural split and balances out some of the east-west variation identified in the residential and workplace patterns. The degree of intra-urban variation remains very high, with per-capita emissions in the highest emission wards up to five times higher than those in the lowest Inner London wards. The very highest emission wards are Heathrow and Gatwick airport, followed by business parks in the Wider Study Area, particularly in the Western Sector.
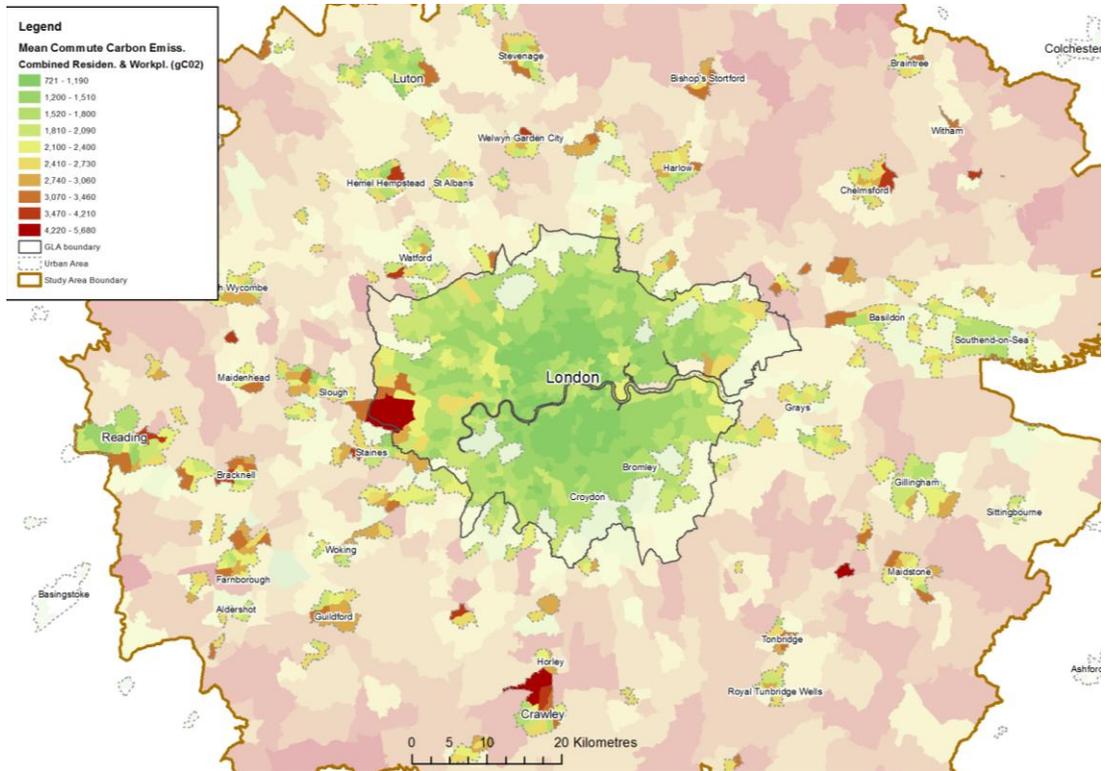
Figure 6.40: Mean Journey-to-Work CO$_2$ Emissions, Combined Residents and Employees 2001.

The analysis of the wider region portrays a favourable picture of Greater London, as London generally features much lower car travel compared to areas beyond the GLA boundary. It is arguable however the extent to which Greater London is directly comparable to the Wider Study Area due to its far superior public transport infrastructure, congested roads and considerably higher density built-environment. Therefore it is informative to analyse Greater London in isolation from the Wider Study Area, as shown in Figure 6.41 using the combined residential-workplace indicator. Note that the legend classification has been adjusted to match the distribution within Greater London, and so is not directly comparable to the previous regional CO$_2$ emissions figures. In Figure 6.41 we get a much more detailed conception of the variation between Central, Inner and Outer London and the performance of major sub-centres. This detailed measure for Greater London provides a useful perspective on the monocentric-polycentric debate, and of current London Plan policies. Arguments stressing the inefficiencies of monocentric structures receive only limited support from this analysis. Whilst travel patterns to Central London are very long distance due to the high levels of employment specialisation, this is

offset by the overwhelming proportions of public transport and pedestrian travel. The Inner City has the lowest travel emissions, with favourable mode-choice and live-work patterns.
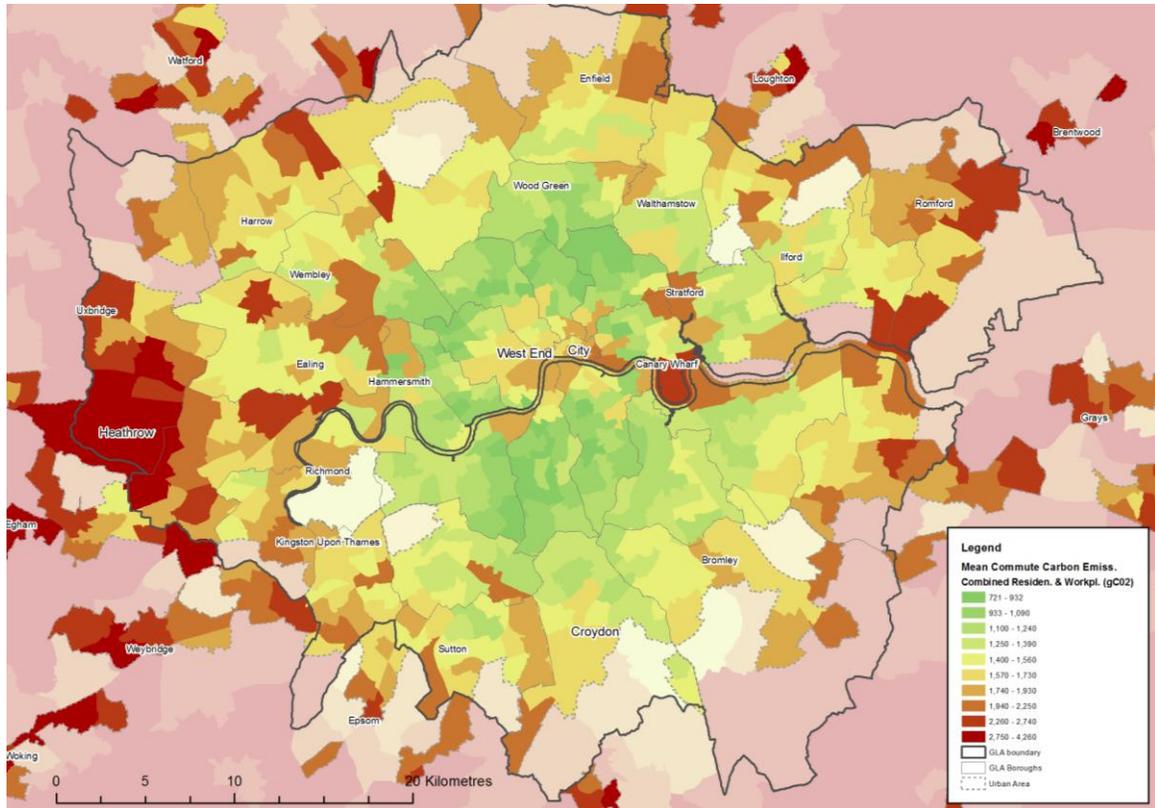
Figure 6.41: Greater London Mean Journey-to-Work CO$_2$ Emissions, Combined Residents and Employees 2001.

The generally benign trends in Central and Inner London contrast with a much more mixed picture for the rest of London's sub-centres. Industrially orientated centres such as Stratford and Park Royal (south-east of Wembley) have higher per-capita emissions, as does Canary Wharf due to its relatively long distance travel patterns and lack of active travel. Canary Wharf is an area of extreme employment change over the last two decades and, given the continued gentrification of East London, it is possible that trip distances will fall over time as residential location patterns adjust. On the other hand, a more critical viewpoint is that the Canary Wharf development is mismatched in terms of scale and socio-economic characteristics from the surrounding urban fabric and that long travel distances are a consequence of this. The lack of pedestrian-only

work travel to Canary Wharf compared to the rest of Inner London (highlighted in Section 6.3) is indicative of a lack of integration with the local area. More recent travel pattern data is needed to resolve this debate. This is an important issue for London as many current developments are following the large scale Inner London clustering approach spearheaded by Canary Wharf, as discussed earlier in Sub-Section 5.3.5.

The picture for Outer London centres is varied and problematic, and therefore the results do not provide strong evidence for promoting more dispersed polycentric employment patterns. South London centres such as Croydon and Sutton achieve the best integration of living and working locations. Moderately high emissions are found in the town centres of Romford and Enfield, while Uxbridge has very high emissions and appears to be failing to function as a town centre in terms of live-work relationships. There are indications of scale effects acting on the efficiency of sub-centres. The wider region analysis pointed to relatively lower per-capita emissions in larger towns such as Reading and Southend. Similarly the largest Outer London sub-centre of Croydon performs relatively well. It could be argued that few of the sub-centres are sufficiently large enough to support significant public transport infrastructure, provide higher-level services and encourage live-work relationships. Not only do sub-centres need to be relatively large, but they also need to be of mixed-use and integrated with the local urban fabric. The two largest sub-centres, Heathrow and Canary Wharf, overwhelmingly fail in terms of local integration judging by this evidence, showing that size can be a negative factor where it results in large scale urban fragmentation. Fragmentation is likely a permanent characteristic of facilities such as airports and industrial parks, whilst more recent evidence is needed to assess whether Canary Wharf is becoming more integrated over time.

6.5.2 CO_2 Emissions Regression Analysis

The CO_2 indicator is essentially a weighted combination of the mode-choice and travel distance patterns analysed in the previous sub-sections. On the one hand, analysing these processes together is useful as there may be synergies between travel distance and mode-choice relationships that are relevant to

planning policy. On other hand, combining mode-choice and travel distances in the same model is somewhat problematic, both conceptually, in terms of whether individuals make residence-workplace location and travel mode decisions together, and practically, in terms of the choices of which independent variables should be included in the regression analysis. The results from the regression analysis are shown in Table 6.6.

Table 6.6: Ward Interaction CO_2 Emissions Model: Goodness-of-Fit and Ranked Coefficients

	5. Per-Capita Flow CO_2 Emissions Trip Cost Variables Only	6. Per-Capita Flow CO_2 Emissions Absolute Trip Cost Var. Excluded	7. Per-Capita CO_2 Emissions All Trip Cost Var. Excluded
Dependent Variable & Goodness of Fit	Regression weighted by flow trip volume	Regression weighted by flow trip volume	Regression weighted by flow trip volume
	R = .910	R = .718	R = .635
	Adjusted R² = .827	Adjusted R² = .515	Adjusted R² = .403

	Coefficient Name	St. β	Coefficient Name	St. β	Coefficient Name	St. β
Coefficients Ranked by Standardised Beta	Flow Distance by Car	.803	Workplace Accessibility to Employ (Rd x=1.7 log)	.591*	Residence Accessibility to Pop. (PT, x=1.7)	-.452
	Flow Relative Car to PT Time (mins faster by car)	.470	Flow Relative Car to PT Time (mins faster by car)	.522	Workplace Accessibility to Employ (Rd x=1.7 log)	.362*
			Residence Accessibility to Pop. (PT, x=1.7)	-.417	Flow Employment Special. 2 (Profess. %)	.287
			Flow Employment Special. 2 (Profess. %)	.230	Workplace Airport Function (% air trans)	.207
			Residence Household Income (ONS estimate)	-.176	Workplace Activity Density (log)	-.195
			Workplace Airport Function (% air trans)	.146	Residence Household Income (ONS estimate)	-.180
			Flow Couple Household (%)	.119	Residence Activity Density (log)	-.162
			Flow Employment Special. 1 (Mange. %)	.091	Flow Couple Household (%)	.124
			Residence Activity Density (log)	-.069*	Flow Employment Special. 1 (Mange. %)	.106
			Workplace Activity Density (log)	-.053	Workplace Commercial Rent (VOA estimate)	.042
			Workplace Commercial Rent (VOA estimate)	.022		

Coefficients significant to 0.99.

*Coefficient has a VIF between 5-10 indicating multi-collinearity (note high collinearity variables with a VIF > 10 removed according to procedure described on page 228).

The choice of which independent variables to use is particularly key in this context. Essentially mode-choice depends on the travel time/distance costs of

the various car and public transport modes available, therefore mode travel times should be included as independent variables to predict mode-choice as part of the emissions regression. Including travel time and distance variables would however remove the influence of any other variables that affect travel distances, such as accessibility and employment specialisation. In consideration of these effects, three versions of the interaction CO_2 emissions model are presented in Table 6.6. Model 5 features distance variables only. This is included to illustrate that the modelled travel CO_2 emissions are comprehensively a result of distance and mode-choice, and subsequently emissions can be largely (R^2 of .827) be predicted using the two flow variables of car distance and relative travel time for car-versus-public transport. The remaining models in Table 6.6 are essentially predicting these underlying distance and mode-choice variables included in Model 5.

In Model 6 the absolute distance variable is substituted with a series of accessibility, built-environment and socio-economic variables that are largely used to predict travel distance. The R^2 value of the model falls to .515 indicating that some, but not all, of the distance variation can be explained. In the final Model 7 the relative car-versus-public transport time variable is also removed, thus the remaining variables need to predict both travel distance and mode-choice, resulting in an R^2 value of .403. Whilst the smaller R^2 value emphasises the difficulties in predicting mode-choice and distance simultaneously, the standardised beta values between the two models follow similar patterns indicating that there are important connections between distance and mode-choice relationships. The accessibility variables are the most significant, with high workplace accessibility to employment increasing emissions whilst being offset by higher residential accessibility to population decreasing emissions. This is the same pattern as the earlier travel distance regression analysis. Employment specialisation variables increase emissions, particularly the professional employment variable which shows high standardised beta values. The airport employment variable again features prominently. The density variables have higher standardised beta values compared to the earlier flow distance model, likely due to their links with car ownership and parking (note that there are multi-collinearity problems between the density and accessibility

variables). The commercial rent variable is correlated with higher emissions, but features less prominently than in the earlier mode-choice and distance models, due to its correlations with long distance trips and public transport travel cancelling each other out in emission terms. Other trends include couple households being connected with higher emission trips, due to dual-worker household and dependent children factors affecting residential location.

6.5.3 Scale, Specialisation and Travel Sustainability of Employment Centres

In this sub-section we connect the travel sustainability analysis from this chapter to the employment centre economic analysis from Chapter 5. The travel sustainability discussion has highlighted the clear tensions between the goals of local sustainable urban travel and the long-distance journeys to specialised centres that define urban regions such as London. Here we return to the employment centre scale of analysis used in Section 5.2, and ask to what extent economic and environmental aims can be reconciled through planning policy. Bearing in mind the accessibility, scale and specialisation relationships revealed in the earlier analyses, the employment centres in the London region (defined in Sub-Section 5.2.4) are graphed according to public transport accessibility and per-capita journey-to-work emissions in Figures 6.42-6.44. Residential emissions are considered in Figure 6.42, whilst Figures 6.43 and 6.44 consider workplace emissions. For residential emissions there is a very strong linear relationship with residential accessibility to employment, with each of the sub-regions grouped on the Figure 6.42 graph according to their accessibility level. The size of the circles indicates the residential population of each centre. Generally larger centres in the wider region, such as Reading, Luton and Slough, have lower residential emissions than comparable centres in their respective sub-regions. On the other hand, there are some exceptions such as Gillingham and Southend. It is generally centres to the east of the Wider Study Area that perform relatively worse due to higher proportions of long distance commuting to Central London, as highlighted in the earlier distance mapping analysis in Section 6.4.

When we switch the focus to employment centre workplace emissions, there are important changes in the relationships, as shown in Figures 6.43 and 6.44. Firstly note that the absolute emission values are much higher (shown on the y-axis), with workplace per-capita emissions varying between 1000-5000 gCO_2, compared to the 100-1200 gCO_2 range for the employment centre residential emissions in Figure 6.48. This is because the highest emission residential trips originate outside of urban areas, whilst the employment centre analysis inherently includes the most significant high-emission employment agglomerations. The clustering by sub-region is also present in workplace emission Figures 6.43 and 6.44 for Central, Inner and Outer London, but in contrast to the residential pattern, the sub-regions beyond the GLA boundary show a massive range of variation in per-capita workplace emissions. Several centres such as Southend and Gillingham are comparable to Central London, whilst centres in the Western Sector generally have around twice the emissions of Central London, and the major airports of Heathrow and Gatwick have around three times higher emissions. The significantly higher average emissions for many centres in the Wider Study Area undermines arguments that sustainable travel patterns can be encouraged through dispersed employment patterns across the region.

Whilst the evidence for sustainable travel patterns in a polycentric framework is in general weak, it is nevertheless worthwhile to explore what characterises the relatively lower workplace emission centres in the wider region. We can ask to what extent larger centres perform relatively better using the data shown in Figure 6.43, where the circle size indicates the number of employees in each centre. For the Greater London sub-regions there is no clear connection, with centre size seemingly unrelated to per-capita emissions. There is however a connection in the Wider Study Area sub-regions, with larger centres such as Southend, Gillingham and Luton displaying lower emissions, whilst Reading (the largest centre outside of the GLA) displays considerably lower workplace emissions than the rest of the Western Sector. We need to put this relationship in the context of employment specialisation, as shown in Figure 6.44 where the circle size indicates centre specialisation in terms of average commercial rental
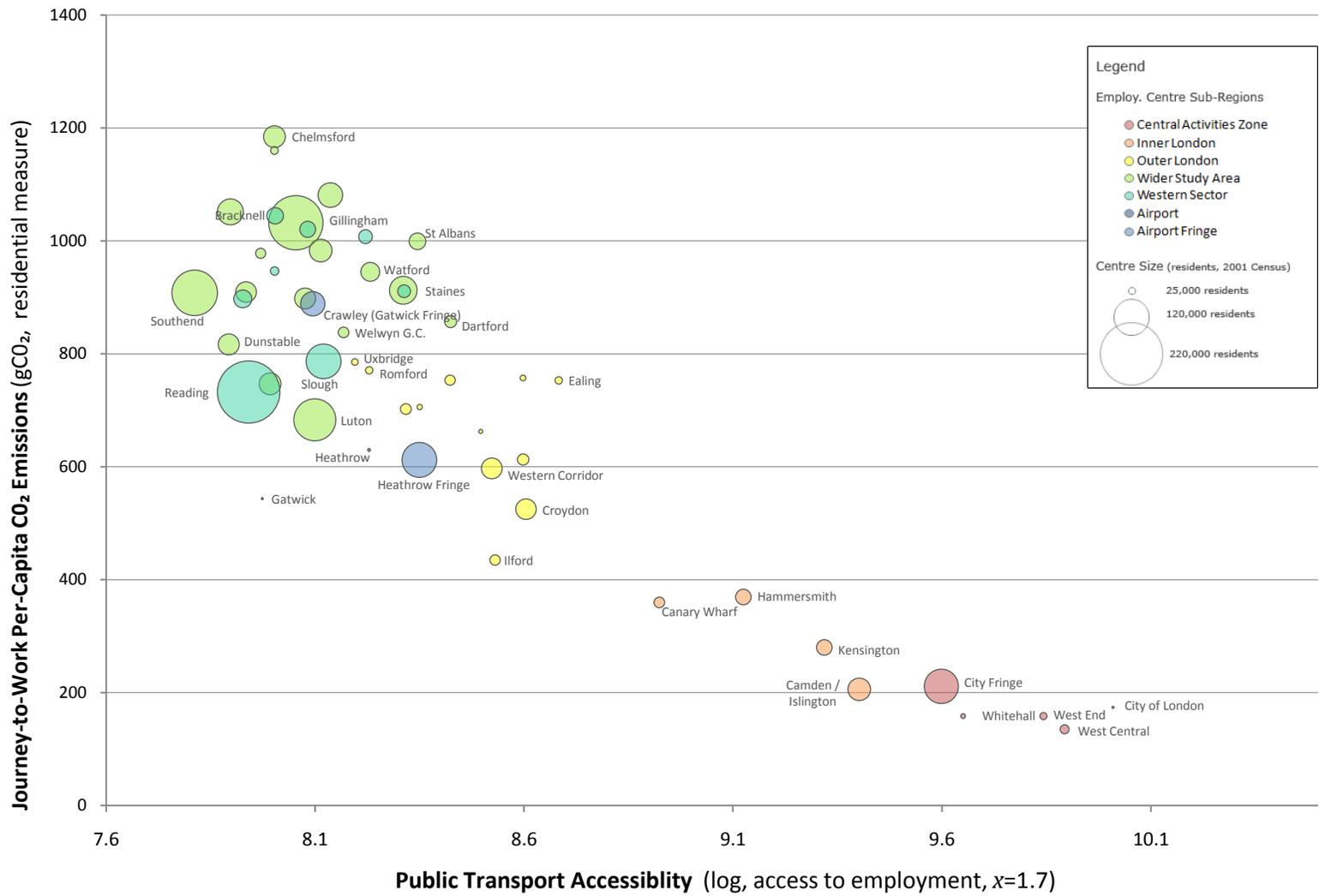
Figure 6.42: Residential Journey-to-Work Emissions, Accessibility and Population Size Graph for London Region Centres
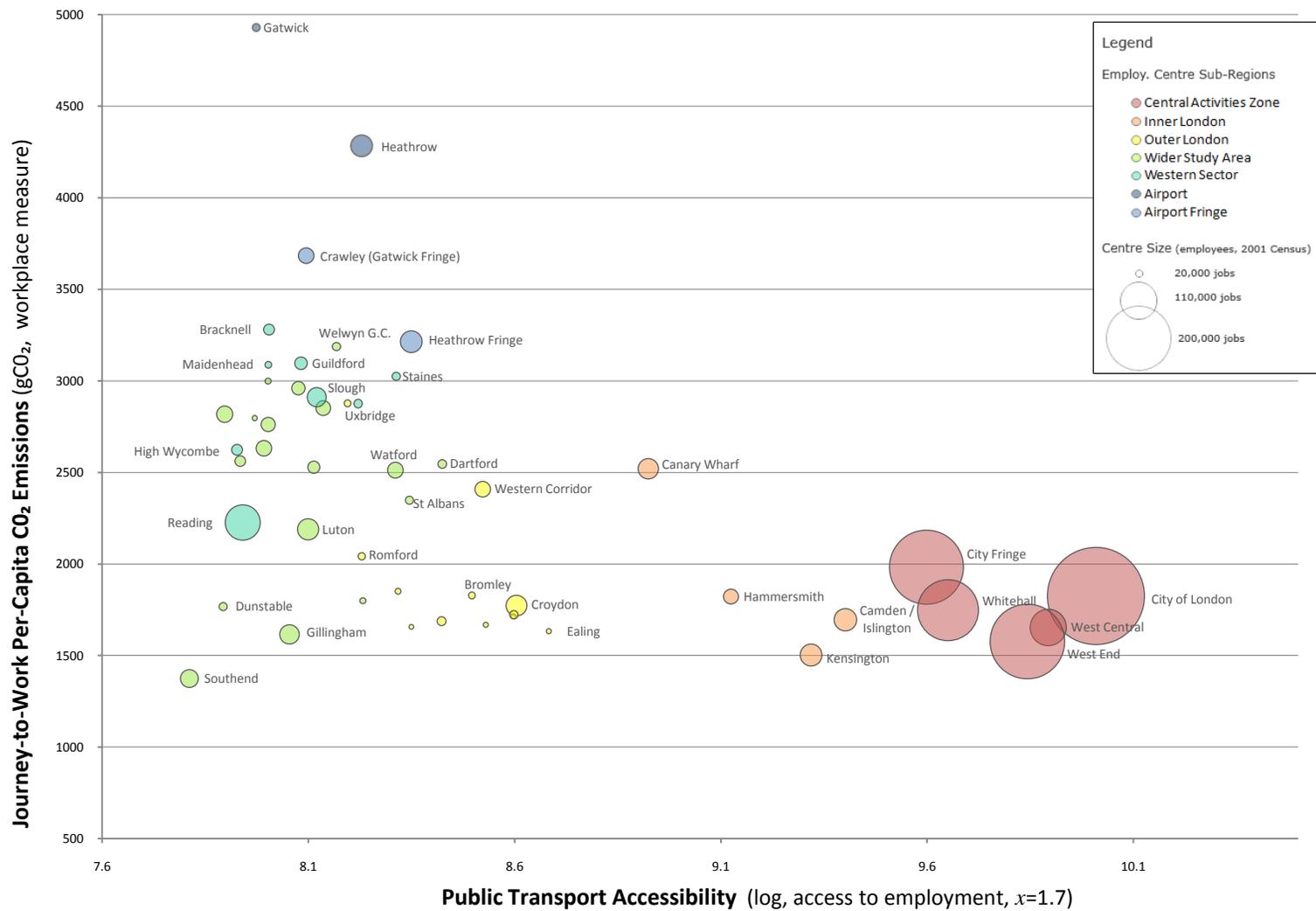
Figure 6.43: Workplace Journey-to-Work Emissions, Accessibility and Employment Size Graph for London Region Centres
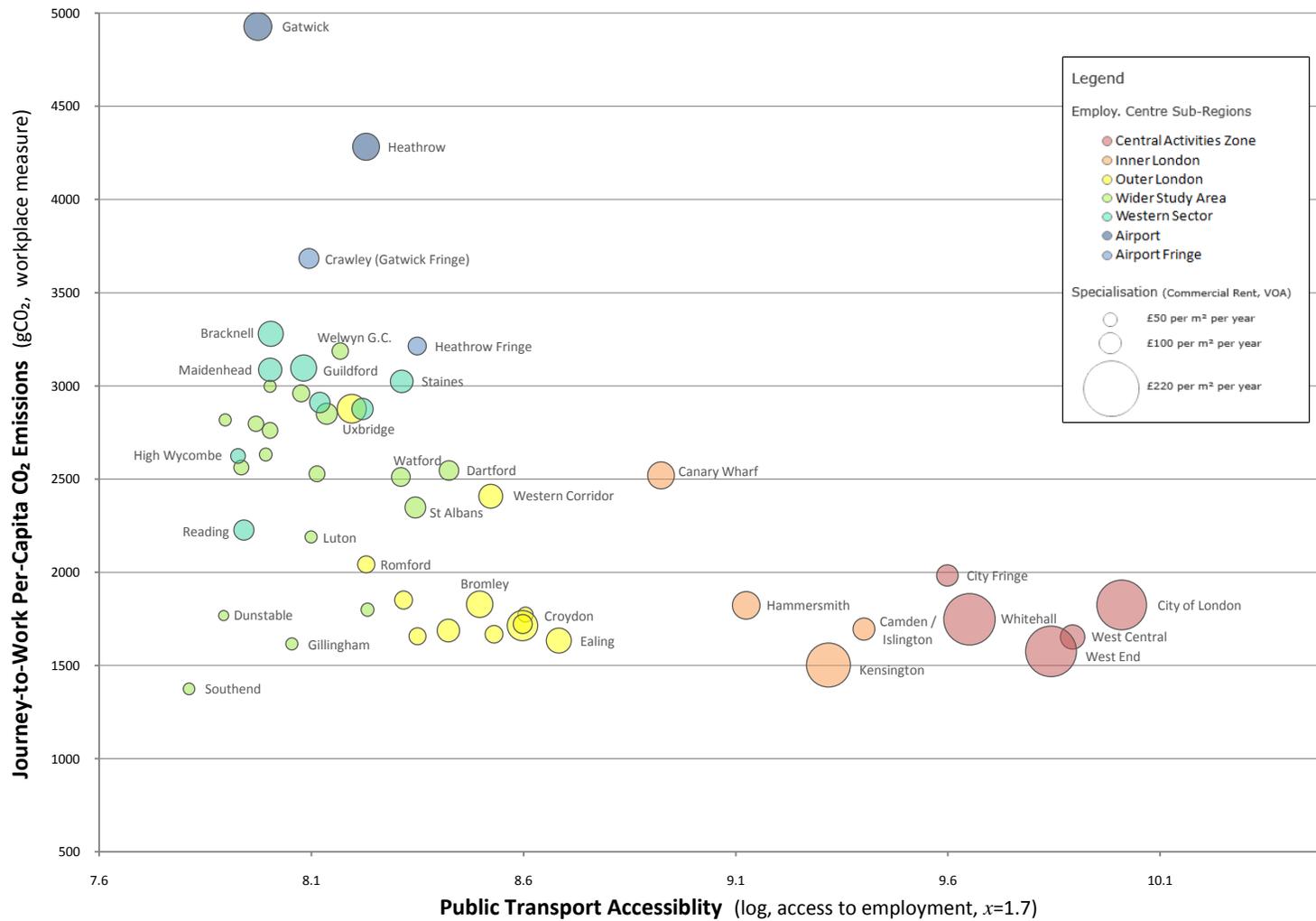
Figure 6.44: Workplace Journey-to-Work Emissions, Accessibility and Specialisation Graph for London Region Centres

value. There is a clear pattern for centres in the Wider Study Area and Western Sector (and to a lesser extent in Outer London) that higher specialisation centres have higher workplace emissions. This pattern somewhat undermines the theory that larger centres encourage sustainable travel (at least in workplace terms), as the larger centre examples of Southend, Luton and Gillingham are all very low specialisation centres, and this is likely to be a major cause of lower workplace emissions in these centres.

These results beg the question of whether or not it is possible for centres to be both relatively specialised and sustainable in locations outside of Inner London. Specialisation is an indicator of economic success and activities in locations such as the Western Sector and Western corridor include highly productive industries for the UK economy (analysed earlier in Section 5.2), industries that it is in the national interest to foster. Examples of specialised centres in the Wider Study area with relatively sustainable workplace travel patterns are largely absent from the study area. Reading is perhaps the only significant example, with moderate emission levels and specialisation. As Reading is the largest centre in the Wider Study Area, this implies there may be scale-related efficiency gains for sub-centres larger than those found in the London Region, though only limited evidence can be gleaned on this issue from the London study area. Another issue to note is that workplace emissions and specialisation vary considerably within Reading itself (Figures 6.39 and 5.19) as there is finer-scale polarisation between the town-centre and edge-of-town business parks.

Overall there is some limited evidence for larger centres in the wider region performing relatively better in travel emission terms, though this relationship must be placed in the context of the stronger influences of public transport accessibility in reducing emissions and employment specialisation in increasing emissions. The ability of Central and Inner London employment locations to achieve a combination of high specialisation and low emission jobs is almost unique in the region, with

high specialisation employment in the wider region overwhelmingly leading to long-distance car travel. Reading is the only significant centre in the wider region to display a limited resolution between the sustainable travel and employment specialisation tensions.

6.5.4 Limitations and Future Improvements for the CO_2 Indicator Methodology

We have illustrated the usefulness of the CO_2 emissions indicator in identifying intra-urban travel pattern variation. There are currently several aspects that limit the accuracy and comprehensiveness of the indicator that could be addressed in future research. These limitations can be grouped into those aspects relating to the underlying datasets, and those aspects relating to the indicator calculation methodology. Regarding the former data issue, an important aspect of the analysis of the London region is that the underlying 2001 Census data is now 10 years old. A series of transportation changes have occurred in London over the last ten years, including improvements to public transport infrastructure, the introduction of the innovative road user charging scheme, and the increased popularity of cycling (TfL, 2010). While the core travel characteristics of the London region have not greatly altered in the last decade, there are likely to have been significant changes for some specific centres. Addressing this issue requires an update of the analysis using the 2011 Census data. This data is not likely to be released until 2013. The analysis of this data would also allow the dynamics of travel sustainability to be considered. Existing studies have considered the sustainability dynamics of cities at aggregate regional scales (Frost and Spence, 2008), and this approach would be complemented by considering finer-scale dynamics. In the London context this is particularly of interest for the newer London centres (such as Canary Wharf and Paddington) where the longer term consequences of major land use policy decisions are still emerging.

A further data issue for this study is that journey-to-work is the only trip purpose that has been considered. This limitation does not result from restrictions of the methodology (as the approach developed is applicable to

any type of travel interaction) but is a limitation of available data. There is currently restricted scope for acquiring a comprehensive and spatially in-depth record of travel patterns for trip purposes other than journey-to-work. A possible route to overcoming this data shortage is to take advantage of advances in the field of smart-card and mobile telephony derived travel interaction data (Reades *et al.*, 2007). The integration of this data with the accessibility and sustainability analyses provided here would be a promising direction for future research to include a wider range of trip purposes. Much additional analysis on the advantages and shortcomings of these new emerging data sources is needed.

In addition to these data issues, there are also some more general assumptions in the indicator calculation methodology that limit accuracy. The methodology assumes that travellers choose the quickest route between origins and destinations. Related to this issue, the accessibility model does not include generalised costs, and is based on travel time. The effect of this limitation is relatively minor due to mode and origin-destination choices being provided by the data rather than being predicted by the model, though the lack of generalised costs may have effects on the supplementary mode-choice patterns in multi-mode public transport journeys. A more significant issue is that the methodology assumes that occupancy levels on public transport services and cars are equal for all journeys across the region (see Sub-Section 4.4.5). This is not the case in reality, particularly for public transport travel. In fact more accurate occupancy figures would likely result in reduced CO_2 emission results for Central and Inner London, as in-bound radial public transport services are generally the most highly overcrowded. The corresponding issue for car trips is that a more accurate methodology for calculating CO_2 emissions would calculate emissions on a road link basis, and include speed-emission curve relationships. This advance to the methodology would require micro-level validation of emissions against average link speeds which is beyond the scope of this thesis, but would be a useful development for future research.

The indicator methodology also assumes that transport infrastructure characteristics, such as the type of cars and trains in use, are standardised across the region. This is likely to be a less problematic assumption. In the future this may not be the case, if for example the take-up of electric cars becomes segmented by income or other socio-economic variables. The issue of how emissions are likely to change given a significant shift in transport infrastructure technology is of great importance in sustainable transportation research, and it would be possible to simulate such scenarios by altering the coefficient values in the CO_2 calculation. Several existing studies have simulated scenarios of changing transport technology (Hickman *et al.*, 2010; Monzon and Nuijten, 2006), and it would be interesting to apply this type of approach at intra-urban scales.

6.6   Chapter Conclusions

The aims of this chapter were firstly to profile the London region in terms of journey-to-work travel sustainability at an intra-metropolitan scale (Research Aim 5ii), and secondly to analyse the main factors influencing journey-to-work behaviour in the study region, in particular the relationships between employment specialisation and journey-to-work sustainability (Research Aim 5iii). For the first research aim, a detailed analysis of journey-to-work mode-choice and travel distance analysis was undertaken, including regional summary data and intra-urban mapping analyses. These mode-choice and distance measures were then combined into a CO_2 emissions indicator which quantifies these trends in terms of a key sustainability measure, and provides an integrated means of assessing intra-metropolitan transport sustainability.

A significant overall conclusion is the importance of the regional perspective provided by the analysis, confirming the urban theory review in Chapter 1 which described increasing regional integration. There are large volumes of travel across the GLA boundary. Employment centres in the wider region are dominated by the car, whilst for those employment centres within Greater London many of the highest emission flows are

from residents outside of the GLA area making long distance trips. Subsequently 50% of all study area CO_2 emissions are for wider region trips, from both residential and from workplace perspectives. It is therefore essential to include the wider region in any comprehensive analysis of travel sustainability in London. The contrasting mode-choice patterns in the wider region are closely connected to accessibility variation as highlighted in the accessibility mapping analysis, with Inner London combining high public transport and restricted car access whilst Outer London and the wider region has strong car access in a number of locations and restricted radial public transport access. Trip destination accessibility in particular came to the fore as the most influential factor in the mode-choice and distance analyses, and this severely undermines any narrowly focussed residential-based trip analysis that excludes the regional context.

A second key characteristic of the travel sustainability results was the degree of variation at intra-urban scales, with intensive variation between employment centres, particularly in terms of trip distances. This variation is driven mainly by the key relationship between high levels of employment specialisation and long distance travel. Additional intra-urban variation comes from differences in employment access for residents (with lower access in the eastern sub-region), and the fragmentation of particular types of centre from their urban context, particularly airports. Thus in answer to Research Aim 5iii, the overall relationship between employment geography and travel patterns is that high specialisation centres significantly increase journey-to-work distances acting through specialised labour markets, higher incomes and the high value commercial agglomerations that price out housing opportunities. These relationships were revealed both in the mapping analysis and in the multivariate regression analyses of trip distances and CO_2 emissions, using the employment specialisation indicators developed in Chapter 5. The regression analyses also confirmed various conclusions from the Chapter 3 review, including the importance of socio-economic variables such as car ownership and household structure, and the overall influence of

accessibility. High accessibility at trip origins reduces emissions whilst being offset by high employment accessibility at trip destinations which increases emissions, due to the link between high employment accessibility and specialised long distance travel. Overall, the main conclusion is that there is a clear tension between localised sustainable travel and the highly specialised regional labour markets that drive long distance travel in the study area.

The CO_2 emissions indicator allows particular employment centres to be profiled and provides evidence for the monocentric-polycentric travel sustainability debate described earlier in Chapter 3 in the context of the London region. Criticisms of the inefficiencies of monocentric structures receive minimal support from this analysis. The long distance travel patterns to Central London are offset by the overwhelming public transport and active travel patterns. This evidence provides support for the largely monocentric growth pattern pursued through the London Plan (see Chapter 5) although there are significant issues with extensive trip distances, long journey times and congestion. The picture for centres in the Wider Study Area and Outer London is highly varied, with some centres such as Croydon achieving good live-work integration, in contrast with the specialised Western Sector, airports and industrial parks which feature the highest per-capita emissions in the region. This evidence generally contradicts the promotion of a more dispersed polycentric approach on sustainable travel grounds. One caveat is that a modest scale effect can be detected with larger towns in the wider region achieving relatively higher levels of public transport use and lower emissions. It is possible that if larger sub-cities were present in the study region then this scale effect would be more pronounced. The current pattern of expansion in the wider region involving growth dispersed amongst small towns and business parks appears to be failing to achieve significant levels of live-work relationships or public transport travel, and does not overcome tensions between specialised employment and sustainable travel patterns.

Conclusions

This research thesis set out to provide an empirical analysis of how changing patterns of employment geography are affecting transportation sustainability in the London region. To answer this research question six detailed research aims were specified in the thesis introduction, and we now revisit these research aims and bring them together in concluding the research.

Research Aim 1 asked "to identify the forces that have changed urban structure and economic geography and resulted in processes of decentralisation". Chapters 1 and 2 reviewed urban geographical theory related to urban spatial change, economic change and to land use transport relationships. We concluded that innovations in transport and communication technology, principally widespread car ownership with further factors such as air transport and digital networks, in combination with increased economic specialisation and globalisation, have greatly increased locational flexibility for firms and residents. These trends have inverted accessibility patterns in traditional monocentric radial cities, enabling economic activities to decentralise and for the regional scope of cities to be greatly extended. In addition to these decentralisation trends, clustering forces from the agglomeration of knowledge economy activities have also been significant influences on urban form. These activities gain productivity advantages, such as knowledge spillovers and shared labour markets, when clustered together and are often attracted to city-centre locations. Urban clustering trends are particularly relevant to major world cities such as London, where knowledge economy industries such as business and financial services are highly concentrated. The combined push and pull of these decentralising and clustering forces is argued to

result in the formation of polycentric urban forms, where economic activities simultaneously decentralise and cluster into specialised multi-nodal city-regions.

These changes in urban economic geography and structure have extensive implications for urban travel patterns and sustainability. Research Aim 2 required that evidence on relationships between urban form and travel sustainability to be reviewed. Travel surveys reveal how populations use transport to maximise their social, employment and other opportunities, with widespread increases in wealth, car ownership and urban decentralisation leading to a five times increase in UK vehicle miles since the 1960's. This trend has severe sustainability impacts, as car travel is significantly more energy and carbon intensive than other modes, and is almost entirely dependent on petroleum, thus creating extensive carbon dioxide emissions and energy security problems. Recent electric vehicle technology could potentially bring significant reductions to private vehicle emissions, but is currently unlikely to make a sufficient impact in the medium term to overcome these sustainability problems (Banister, 2005). Therefore policy should remain focussed on restricting car use and promoting public transport and active travel. The framework of basing transport sustainability assessment on mode-choice and travel distance patterns was applied throughout the research.

The analysis of relationships between urban spatial structure and travel sustainability concluded that multiple urban dimensions collectively contribute to travel pattern outcomes, including socio-economic, built-environment, infrastructure and technology factors. Cities that achieve relatively sustainable travel patterns achieve synergies between these urban dimensions. Socio-economic factors are often amongst the most influential in statistical analyses, with income and fuel taxation strongly correlated at city-scales whilst car ownership and household structures are influential at individual scales. Built-environment factors such as density and mixed land uses are generally a necessary but not sufficient condition of more sustainable travel patterns. These built-environment factors affect

travel behaviour through influencing accessibility- the ease by which residents can access opportunities by different transport modes. Regional accessibility was found to be the most influential variable in a meta-analysis of disaggregate studies (Ewing and Cervero, 2010). This provides an important link between theory and evidence, as the significance of regional accessibility corresponds with the increasing urban regional integration predicted by polycentric urban theory. The evidence showing the importance of regional integration undermines travel sustainability studies that lack a regional scope, yet the research review found relatively few studies tackling issues of changing regional employment geography and travel patterns. Those studies that did take this approach identified mode-choice changes occurring with decentralisation processes (Cervero and Wu, 1997; Titheridge and Hall, 2006). The link between agglomeration and travel patterns has not been made in the literature, and therefore this research addresses a significant research gap between urban economic geographical theory and travel sustainability research. To tackle this research problem we argued that an intra-metropolitan meso-scale analysis is required; in-between the more frequently analysed micro and macro urban scales. This intermediate scale allows consideration of intra-urban variation in socio-economic geography and travel patterns, whilst including the regional scope that increasingly defines contemporary cities. This is the appropriate scale from which to analyse the travel sustainability of decentralised and polycentric forms for planning policy.

The next step in the research (Research Aim 3) was to develop the methodology for the empirical intra-metropolitan analysis of urban form, economic geography and transport sustainability. The review of urban location theory stressed the importance of measuring socio-economic geography and the built-environment together when seeking to understand urban form, and capturing their interrelationships and dynamics. The indicators developed in this research included urban form, accessibility and travel pattern measures as well as new employment specialisation indicators. The concept of employment specialisation was critical as it provides a link between economic geography and property markets

(through agglomeration economy processes) and potentially provides a link between economic geography and travel patterns- i.e. the key relationship that this research analyses. The intra-metropolitan scale of analysis pursued here for the calculation of these indicators is technically challenging due to the trade-off between extent and level-of-detail that is common in geographical analysis. New datasets and methodological innovations were developed to seek to overcome this trade-off, including the use of detailed business survey data to measure fine-scale employment geography; the use of real-estate data to analyse the built-environment and property markets; improvements to accessibility measures using detailed network analysis and timetable data; and finally the development of an intra-urban travel CO_2 emissions indicator. These indicators all use national UK datasets to allow their translation into other urban contexts (discussed further below). The intra-metropolitan approach is very demanding in data terms and this led to shortcomings in the analysis of the London region, particularly the restriction of the travel sustainability analysis to journey-to-work travel for the year 2001.

Following the development of the methodology, the indicators were then calculated for the study area of the London region, firstly answering Research Aim 5i on the structure and dynamics of London's economic geography and the extent to which this geography can be classified as polycentric. The analysis identified stark agglomeration patterns across the region connected to intensive variation in employment growth, specialisation and urban development indicators. The methodology was successful in capturing strong intra-metropolitan trends in economic geography, confirming the value of the meso-scale approach. The overall pattern for Greater London showed that the growth of business services, finance and tourism has overwhelmingly benefitted Central and Inner London, with these industries strongly agglomerated in the city-centre. This growth has been fundamentally enabled by built-environment intensification, with London Plan policy and real-estate investment seeing 75% of new GLA office space in the last decade within the Central Activities Zone. This is in combination with substantial radial

transportation infrastructure upgrades. Thus the growth pattern in Greater London is strongly monocentric. There is an additional trend of high density inner-city clustering at tertiary locations such as Canary Wharf and Paddington Basin.

Yet this is not the whole picture, as the analysis identified particular knowledge economy industries- such as IT, media and defence industries- that are clustered beyond Inner London in the wider region, particularly to the west in the Western Sector and Western Corridor. Another peripheral growth trend is the expanding role of airports as major employment hubs. The overall impact of these trends is that growth rates in the wider region have exceeded Greater London growth rates in the last two decades. Furthermore cross-border journey-to-work interactions are substantially increasing, particularly reverse commuting, confirming the trends predicted by polycentric urban region theory of increasing regional integration. Thus at the regional level monocentric and polycentric urban growth trends are occurring simultaneously. Growth patterns are highly specialised, segmented by economic sectors and arranged around sub-regional clusters and transportation infrastructure hubs. These specialised growth patterns have a distinct downside for areas that fall outside of the sub-regional knowledge industry clusters. Outer London has suffered from continued manufacturing decline and back-office restructuring, losing jobs in the last decade. Policy measures have failed to achieve significant growth in key Outer London locations such as Croydon.

The next aim for the intra-metropolitan analysis of the London region was to profile the journey-to-work travel sustainability in the study area (Research Aim 5ii), and to analyse the relationships between economic geography and travel sustainability (Research Aim 5iii). Like the employment geography analysis, the regional perspective was pivotal in the results, with dramatic contrasts in accessibility and mode-choice between London's urban core, which is dominated by public transport and suppresses car travel, and the wider region, which has restricted radial public transport and much faster and more flexible car accessibility. The

CO_2 emissions analysis showed that journey-to-work trips in the wider region, from either residential or workplace perspectives, accounted for 50% of all the emissions in the study area, thus a regional scope is essential for any comprehensive analysis. The regression results highlighted the key role of trip destination factors in determining mode-choice, agreeing with conclusions from other studies (Badoe and Miller, 2000; Ewing and Cervero, 2001) and providing further support for the intra-metropolitan approach which can analyse trip origin and destination factors simultaneously.

Alongside the regional variation, the results revealed intensive intra-urban variation, particularly in trip distances, closely linked to the employment specialisation patterns. High specialisation centres lead to long distance travel due to specialised labour markets, high income, and expensive property markets which limit housing opportunities. Less specialised jobs are characterised by local labour markets and closer live-work relationships. These trends result in very long distance travel to Central London as well as other specialist agglomeration areas such as the Western Sector. Furthermore long distance travel is also associated with large facilities with fragmented urban land uses, such as industrial parks and particularly airports. The major airports have by far the highest per-capita and absolute CO_2 emissions in the entire study region. Travel sustainability trends can also be viewed from the residential perspective, where overwhelmingly more sustainable travel comes from urban residents compared to rural residents particularly for urban residents in larger cities, confirming existing research on city size and travel sustainability (ECOTEC, 1993; Banister, 2005). Longer distance travel also comes from residents in sub-regions isolated from job opportunities (again in line with regional accessibility perspectives), which in the study area refers particularly to the eastern part of the wider region.

The overall conclusion is that there are clear tensions between the aims of localised sustainable travel patterns and the specialised regional labour markets that increasingly define cities like London. The multiple

specialised centres that are the core of the London region economy are defined by long distance journey-to-work patterns. The monocentric structure of Greater London achieves very high levels of public transport and active travel, thus intensification policies are effective on sustainable travel grounds (though have problems with long duration trips for workers and high levels of congestion). Meanwhile specialised jobs outside of the city centre are connected to long distance car dominated commuting. No other centres outside of Central London comprehensively resolve this specialisation-sustainability tension. The centres that come closest are the larger sub-centres, such as Reading and Croydon, which achieve more localised travel patterns and a modest degree of public transport travel. Potentially larger sub-centres than these would accentuate this sustainability scale-effect, though larger sub-centres are not found in the study area. The current pattern in the wider region of diffused growth between small towns is failing to achieve co-location and is linked to poor sustainable travel performance. This is a very significant planning challenge for the London region given the higher growth rates beyond the GLA boundary.

7.1.1 Implications for the Understanding of Polycentricity

We argued that polycentricity is a scale dependent concept that reflects the dominance of centres within a central place hierarchy structure. The results showed that in absolute employment terms the London region remains largely monocentric, and is in fact re-establishing the historic monocentric structure with strong intensification trends within Greater London. Yet locational patterns were shown to be distinct between economic sectors, and there are highly productive knowledge economy agglomerations located in the wider region. There is therefore a degree of functional polycentricity in the wider London region, with specialised sub-regions in industries such as IT and research. These conclusions emphasise how monocentricity and polycentricity should be considered in the context of different specialised economic functions, as these have highly contrasting locational patterns. The scale dependence of these concepts was also emphasised, with contrasting results at different scales. Fine-grained built-

environment analysis revealed inner-city nodal polycentricity in Greater London. More aggregate Greater London analysis emphasises the dominance of the inner-city. Finally the regional analysis highlighted more dispersed growth beyond the GLA boundary in addition to the monocentric pattern. These varied trends at different scales of analysis are connected to planning policy and the various scales at which agglomeration economy processes are functioning.

In terms of the empirical analysis of polycentricity and related concepts of monocentricity and decentralisation, a method was developed using combined clustering and centralisation statistics. The Getis-Ord General G statistic was found to be particularly useful for differentiating between urban clustering pattern, compared to the more commonly applied Moran's I statistic which was less effective. These measures are applicable both at the aggregate level and to specific sectors, and thus allowed the analysis of the contrasting locational patterns between economic sectors described above.

7.1.2   Policy Implications for London and the Wider Region

Building on the above conclusions regarding sustainable travel and urban form, we now consider the implications of the research for planning policy in the London region, in terms of whether or not policy is guiding the London region towards more sustainable structures. In the first instance planning policy has been highly successful in facilitating the boom and intensification of Central London up to the recent economic recession. This outcome has largely achieved both economic and sustainable travel aims, with moderately-low emissions calculated for the city-centre, especially considering the highly specialised knowledge economy jobs that are present. The main concerns with this policy relate to congested public transport, lack of housing supply and the subsequent long duration of trips for commuters. Given the overall success of central intensification policies, the remaining issues of debate are the challenges of the Outer London Centres with mixed economic and sustainability performance, and

the lack of coordinated regional policy beyond the Greater London Authority boundary.

Within the GLA boundary, the key economic development and urban form outcomes over the last two decades have been the nodal development of high density inner-city clusters, and the stagnation of growth in Outer London (except in the context of Heathrow). Most of the recent growth in Greater London has taken the form of large-scale nodal inner-city development, with Canary Wharf being the prime example, followed by Paddington and White City over the last decade, and with further large scale development underway at locations such as Stratford and Kings Cross. This represents an emerging structure of inner-city nodal polycentricity. These centres have been successful economically in attracting developer investment and in meeting the demands of firms for office locations. In sustainable travel terms, centres such as Canary Wharf and White City also achieve high levels of public transport use. The main problem appears to be a lack of integration with the local urban environment, particularly at Canary Wharf, where a low proportion of the workers live in the local area. More recent data is needed to see if this is an issue that has been curtailed with evolving residential and gentrification patterns in East London, or whether there is a permanent mismatch of scale and lack of integration with the local urban context. Overall the results indicate that high-density nodes need to be planned as part of wider urban districts with a range of housing opportunities that can facilitate live-work relationships. Similar issues of local fragmentation are found in a more extreme context at airports. These have by far the highest per-capita and total journey-to-work emissions in the entire study region. This is a significant issue given the major expansion of airports (and linked employment developments) over the last decade, as well as the many further environmental impacts that result from air-travel in general. This evidence supports planning policy moves to improving public transport access to major airports such as Heathrow, potentially in combination with restricted car access.

Overall planning policy within Greater London has been mostly successful in directing growth to high-density public transport nodes, largely in accordance with mainstream sustainable urban planning theory. The major challenges for planning policy are arguably not occurring in Greater London at all, but in the wider region. Growth beyond the GLA boundary is higher in percentage terms than Inner London, and is also comparable in absolute terms to the GLA as a whole. Journey-to-work trips across the GLA boundary continue to increase and are amongst the highest in per-capita emission terms in the study area, agreeing with the conclusions from Frost and Spence (2008). The specialised jobs in areas such as the Western Sector lead to long distance car commuting with minimal live-work relationships, despite these being mixed-use towns. These towns have limited housing supply and may be perceived as lacking the services and public realm quality to attract affluent workers to settle. The evidence from this research points to more efficient regional expansion being achieved by directing growth (particularly of specialised knowledge economy industries) to larger more clustered towns and cities that can support public transport services and have sufficient facilities and housing opportunities to encourage live-work relationships. This would be most straightforward to achieve by concentrating growth in existing centres, such as Reading and Croydon. These policies require a greater degree of regional planning integration than is currently in place given the lack of regional government structures outwith the GLA. The weak regional planning framework has lead to the fragmented growth pattern currently occurring. This conclusion of prioritising the expansion of larger towns and cities over smaller settlements also applies to the results from the residential analysis, where far higher journey-to-work emissions occurred from residents in isolated rural wards. Certainly the expansion of the Greater London population with more housing opportunities would minimise travel emissions compared to a dispersed regional population expansion.

A major strategy of the London Plan is the regeneration of East London. The effects of regeneration policies were not identified in this analysis

beyond the established Docklands developments due to the long term nature of these regeneration policies, and that much of the data analysis relates to the year 2001. One important issue that did emerge however was that the lack of sub-regional job opportunities to the east of the study region. This pattern has sustainable travel consequences, with long distance commutes in the eastern part of the wider region. Eastern expansion in employment opportunities would potentially lead to a more balanced geography of jobs and housing, rather than the problems of the overheating property markets to the west and lack of jobs in the east that is the current situation. A caveat though is that the Canary Wharf development displays limited local interactions as discussed above and developments need a higher degree of integration with their local urban context to facilitate sustainable travel patterns.

7.1.3   Commentary on the Indicators Developed

A series of indicators were developed for the analysis of economic geography, urban form, accessibility and travel sustainability. Here the most useful indicators are identified and future application areas for these measures are discussed.

For the analysis of employment geography, the multiple dimensions of employment specialisation were shown to be closely linked, including sectoral and occupational class clustering and high commercial property rents. The close integration of these indicators confirms urban location theory. The occupational class and rent indicators were the most broadly applicable and easiest to calculate. These indicators would be useful in economic geography studies of agglomeration economies, and, as this research has shown, could be used by planners in linking knowledge economy clusters to travel patterns. The commercial rental indicator identifies attractive and overheating property markets, which is useful in analysing urban development and real-estate investment. Similarly the urban form floorspace measures would also be useful in an urban development research context. The detailed industrial sector analysis was

also revealing in highlighting clusters of specific industries. This analysis was more time consuming to calculate and cannot be simplified into a single measure in the manner of the other employment specialisation indicators.

For the accessibility indicators, the results pointed to the public transport accessibility indicators having the strongest links to travel patterns, as these were connected with high public transport and restricted car access. In particular the destination accessibility measure proved to be highly influential in both reduced car trips and increased trip distances (through the connection to employment specialisation). The accessibility indicators are however very time consuming to calculate, particularly at an intra-metropolitan scale, as they are matrix based, and require substantial network analysis.

The CO_2 emissions indicator summarises mode-choice and trip distance information into a comprehensive indicator of urban travel sustainability. It is considerably more representative than traditional indicators such as self-containment measures, and also has advantages over vehicle miles travelled indicators as public transport emissions are included. The indicator is close to the energy emissions indicator developed by Frost and Spence (2008), with the main difference being the intra-metropolitan geographical scale rather than aggregate urban scale developed in this research. The CO_2 emissions indicator is potentially applicable in many research contexts, and would be a particularly useful addition to integrated urban assessment tasks. The detailed network routing and multi-modal travel flows allow more realistic representation of journeys and their impacts, and the mapping analysis and tables showed how trends could be analysed at various scales. This indicator depends on the above accessibility analysis routing and so is again not straightforward to calculate. Furthermore it is relatively demanding in terms of data. Data availability has significantly influenced choices in the trip purpose considered (journey-to-work) and the year of the study (2001) in this research. Time-series analysis will be possible with the forthcoming

release of the 2011 census. In terms of considering other trip purposes, no other dataset as comprehensive as the census is likely to become available. Techniques utilising smartcard and mobile telephony data are a promising direction for future research to include a wider range of trip purposes. In addition to these data limitations, the indicator methodology accuracy would be improved with micro-level validation to test the performance of the emission coefficients against detailed individual journey measures, replacing the average emission values with specific road link and public transport service emission factors.

7.1.4   Application of the Research Methods to Other Cities

The application of the intra-metropolitan indicators and analysis methods has been restricted in this research to the London region. Certainly it would be valuable to apply these methods in other urban contexts to allow a much broder perspective of intra-metropolitan geography and compare trends in London with other city-regions. Particular questions that emerged in the research, such as whether London trends are distinct from other major world cities and whether sustainability gains would be made with larger regional sub-centres, cannot be answered by examining London alone. The approach used in this research to develop the indicators and analysis deliberately focussed on national UK datasets, thus it would very straightforward to apply these indicators to other UK cities. Such studies including multiple UK cities would be useful to contrast sustainable travel trends in the context of variable city size and economic performance, as pursued by Frost and Spence (2008) at an aggregate level for London, Manchester and Birmingham.

The application of the methods in an international context would require a greater degree of translation, as different countries have varied standards for datasets such as industrial classifications, property valuation and census statistics. Generally the UK is in a strong position for data collection and availability. Yet similar datasets are widely available in other countries, particularly in European and North American contexts,

and indeed some US datasets are more detailed with data such as income included which is absent in the UK. The current trend towards open data standards is also potentially a great boost for comparative urban analysis, with pan-European trends towards open government sites such as the London Datastore and Paris Data websites. The most interesting studies would be to compare London to similar world city-regions such as Paris and New York. Also examples of extreme polycentricity, such as the Ranstad in the Netherlands would provide a much broader context to sustainable travel research. Indeed this was the approach taken in the innovative Polynet study (Hall and Pain, 2006), although this did not provide the detailed intra-metropolitan indicators and travel sustainability analysis pursued here. The continuation of the intra-metropolitan analysis for more world cities would be a very fruitful direction for future research.

References

Adams, J.S. (1970), 'Residential structure of mid-western cities', *Annals of the Association of American Geographers,* 60: 37-62.

Al-Juaied, M. and Whitmore, A. (2009), *Realistic costs of carbon capture,* Belfer Centre for Science and International Affairs, Cambridge, MA.

Alberti, M. (1996), 'Measuring urban sustainability', *Environmental Impact Assessment Review,* 16: 381-424.

Alonso, W. (1964), *Location and Land Use: Toward a General Theory of Land Rent,* Harvard University Press, Cambridge, MA.

Anas, A. (1982), *Residential location markets and urban transportation: economic theory, econometrics and policy analysis with discrete choice models,* Academic Press, New York.

Anas, A., Arnott, R. and Small, K.A. (1998), 'Urban Spatial Structure', *Journal of Economic Literature,* 36(3): 1426-1464.

Arthur, W.B., Ermoliev, Y.M. and Kaniovski, Y.M. (1987), 'Path-dependent processes and the emergence of macro-structure', *European Journal of Operational Research,* 30: 294-303.

Atkinson, R. (2004), 'The evidence on the impact of gentrification: new lessons for the urban renaissance?' *European Journal of Housing Policy,* 4(1): 107-131.

Atisreal and Geofutures (2005), 'Property value study – Assessing the changes in value attributable to the Jubilee Line Extension', Transport for London, London.

Badoe, D.A. and Miller, E.J. (2000), 'Transportation-land-use interaction: empirical findings in North America, and their implications for modelling', *Transportation Research Part D,* 5: 235-263.

Banister, D. (2005), *Unsustainable transport: city transport in the new century,* Routledge, London, UK.

Banister, D., Watson, S. and Wood, C. (1997), 'Sustainable cities: transport, energy, and urban form', *Environment and Planning B: Planning and Design,* 24(1): 125-143.

Batty, M. (1994), 'A chronicle of scientific planning: the Anglo-American modelling experience', *Journal of the American Planning Association,* 60(1): 7-16.

Batty, M. (2000), 'The new urban geography of the third dimension', *Environment and Planning B: Planning and Design,* 27: 483-484.

Batty, M. (2001a), 'Models in planning: technological imperatives and changing roles', *International Journal of Applied Earth Observation and Geoinformation,* 3(3): 252-266.

Batty, M. (2001b), 'Polynucleated urban landscapes', *Urban Studies,* 38(4): 635-655.

Batty, M. (2004), *A new theory of space syntax,* Centre for Advanced Spatial Analysis, University College London, London.

Batty, M. (2007a), 'Model cities', *Town Planning Review,* 78(2): 125-178.

Batty, M. (2007b), *Visualising creative destruction,* Centre for Advanced Spatial Analysis, University College London, London.

Batty, M., Bessusi, E., Maat, K. and Haarts, J. (2003), *Representing multifunctional cities: density and diversity in space and time,* Centre for Advanced Spatial Analysis, London.

Batty, M., Carvahlho, R., Hudson-Smith, A., Milton, R., Smith, D.A. and Steadman, P. (2008), 'Scaling and allometry in the building geometries of Greater London', *European Physical Journal B,* 63(3): 303-314.

Batty, M., Chapman, D., Evans, S., Haklay, M., Kueppers, S., Shiode, N., Hudson-Smith, A. and Torrens, P.M. (2001), 'Visualizing the city: communicating urban design to planners and decision-makers', in Brail, R.K. and Klosterman, R.E. (eds.), *Planning Support Systems: Integrating Geographic Information Systems, Models and Visualisation Tools*, ESRI Press, Redlands, CA, pp. 405-443.

Batty, M. and Hudson-Smith, A. (2002), 'Virtuality and cities: definitions, geographies, designs', in Fisher, P. and Unwin, D. (eds.), *Virtual Reality in Geography*, Taylor & Francis, London, UK, pp. 270-291.

Batty, M. and Longley, P.A. (1994), *Fractal cities: a geometry of form and function,* Academic Press, London, UK.

Beaverstock, J.V., Taylor, P.J. and Smith, R.G. (1999), 'A roster of world cities', *Cities,* 16(6): 445-558.

Ben-Akiva, M. and Lerman, S.R. (1985), *Discrete choice analysis,* MIT Press, Cambridge, MA.

Bertaud, A. (2002), 'Note on transportation and urban spatial structure', *Annual Bank Conference on Development Economics*, Washington, D.C.

Breheny, M. (1995), 'The Compact City and transport energy consumption', *Transactions of the Institute of British Geographers,* 20(1): 81-101.

Breheny, M. (1997), 'Urban compaction: feasible and acceptable?' *Cities,* 14(4): 209-217.

Bruhns, H. (2000), 'Property taxation data for nondomestic buildings in England and Wales', *Environment and Planning B: Planning and Design,* 27: 33-49.

Buchanan, C.D. (1963), *Traffic in towns,* HMSO, London.

Carson, R. (1962), *Silent spring,* Houghton-Mifflin, Boston.

Castells, M. (2000), *The information age: economy, society and culture: Volume I, the rise of the network society (2nd),* Blackwell, Oxford.

Castells, M. and Hall, P. (1994), *Technopoles of the world: the making of 21st century industrial complexes,* Routledge, London.

Cervero, C. (2002), 'Built environments and mode choice: toward a normative framework', *Transportation Research Part D,* 7: 265-284.

Cervero, R. (1989), 'Jobs-housing balancing and regional mobility', *Journal of the American Planning Association,* 55(2): 136-150.

Cervero, R. (1996a), 'Jobs-housing balance revisited: trends and impacts in the San Francisco Bay Area', *Journal of the American Planning Association,* 62(4): 492-511.

Cervero, R. (1996b), 'Mixed land-uses and commuting: evidence from the American Housing Survey', *Transportation Research Part A,* 30(5): 361-377.

Cervero, R. (1998), *The transit metropolis: a global inquiry,* Island Press, Washington, D. C.

Cervero, R. and Wu, K.L. (1997), 'Polycentrism, commuting and residential location in the San Francisco Bay Area', *Environment and Planning A,* 29(5): 865-886.

Chadwick, E. (1842), *Report on the sanitary conditions of the labouring populations of Great Britain,* Edinburgh University Press, 1965, Reprinted: Edinburgh, Scotland.

Chadwick, G. (1971), *A systems view of planning: towards a theory of the urban and regional planning process,* Pergamon, Oxford, UK.

Chen, C., Gong, H. and Paaswell, R. (2008), 'Role of the built environment on mode choice decisions: additional evidence on the impact of density', *Transportation,* 35: 285-299.

Christaller, W. (1933), *Central places in Southern Germany,* Fischer, Jena, Germany.

Coe, N.M. and Townsend, A.R. (1998), 'Debunking the myth of localized agglomerations: the development of a regionalized service economy in South-East England', *Transactions of the Institute of British Geographers,* 23(23): 385-404.

Coffey, W.J. and Bailly, A.S. (1992), 'Producer services and flexible production', *Urban Studies,* 29(6): 857-868.

Conzen, M. (1960), *Alnwick, Northumberland: a study in town-plan analysis,* Institute of British Geographers, London.

Cook, G.A.S., Pandit, N.R., Beaverstock, J.V., Taylor, P.J. and Pain, K. (2007), 'The role of location in knowledge creation and diffusion: evidence of centripetal and cetrifugal forces in the City of London financial services agglomeration', *Environment and Planning A,* 39(6): 1325-1345.

Cullingworth, B. and Nadin, V. (2006), *Town and country planning in the UK (14th),* Routledge, Abingdon, Oxon.

Davoudi, S. (2003), 'Polycentricity in European spatial planning: from an analytical tool to a normative agenda', *European Planning Studies,* 11(8): 979-999.

de Smith, M.J., Goodchild, M.F. and Longley, P.A. (2007), *Geospatial Analysis: A Comprehensive Guide to Principles, Techniques and Software Tools (2nd Edition),* The Winchelsea Press, Winchelsea, UK.

Department for Business Enterprise and Regulatory Reform (2007), *UK Energy Flow Chart 2007*, Department for Business Enterprise and Regulatory Reform, London.
URL: http://www.decc.gov.uk/en/content/cms/statistics/publications/flow/flow.aspx

Department for Environment Food and Rural Affairs (2009), *Sustainable development indicators in your pocket,* DEFRA, London.

Department for Environment Food and Rural Affairs (2010), *2008 guidelines to DEFRA / DECC's GHG conversion factors for company reporting: methodology paper for emission factors,* DEFRA, London.

Department for Transport (2008), *National Travel Survey,* National Statistics, London.

Department for Transport (2009a), *Low carbon transport: a greener future,* Department for Transport, London.

Department for Transport (2009b), *Transportation statistics Great Britain,* The Stationary Office, London.

Department for Transport (2009c), *Transportation trends 2009 edition,* The Stationary Office, London.

Department for Transport (2010), *TransXChange Schema Guide 2.4,* Department for Transport, London.

Department of Energy and Climate Change (2009), *UK low carbon transition plan emissions projections,* DECC, London.

Department of the Environment (1994), *Transport Planning Policy Guidance Note 13,* HMSO, London.

Department of the Environment (1997), *Planning Policy Guidance 1: general policies and principles,* HMSO, London.

Dijkstra, E.W. (1959), 'A note on two problems in connexion with graphs', *Numerische Mathematik,* 1(1): 269-271.

Duranton, G. and Puga, D. (2001), *From sectoral to functional urban specialization,* Centre for Economic Policy Research Working Paper No.2971.

ECOTEC (1993), *Reducing transport emissions through planning,* HMSO, London.

Ecourier (2007), *Courier vehicle delivery GPS data [computer file]*, Ecourier, London. URL: api.ecourier.co.uk.

Ewing, R. and Cervero, R. (2001), 'Travel and the built environment: a synthesis', *Transportation Research Record,* 1780: 87-114.

Ewing, R. and Cervero, R. (2010), 'Travel and the built environment', *Journal of the American Planning Association,* 76(3): 265-294.

Fagerberg, J. (2003), 'Schumpeter and the revival of evolutionary economics: an appraisal of the literature', *Journal of Evolutionary Economics,* 13: 125-159.

Firebaugh, G. and Gibbs, J. (1985), 'User's Guide to Ratio Variables', *American Sociological Review*, 50(5): 712-722.

Foster, J. (1999), *Docklands: cultures in conflict, worlds in collision,* UCL Press, London.

Frank, L.D. and Pivo, G. (1994), *Relationships between land use and travel behaviour in the Puget Sound region,* Washington State Department of Transportation, Seattle.

Freeman, L.C. (1977), 'A set of measures of centrality based on betweenness', *Sociometry,* 40(1): 35-41.

Frost, M. and Spence, N. (2008), 'Energy consumption and work-travel trips: London, Birmingham and manchester, 1981-2001', *Environment and Planning A,* 40(9): 2238-2258.

Fujita, M. and Thisse, J.F. (1996), 'Economics of agglomeration', *Journal of the Japanese and International Economies,* 10(4): 339-378.

Garreau, J. (1991), *Edge city: life on the new frontier,* Doubleday, New York.

Getis, A. and Ord, K. (1992), 'The analysis of spatial association by use of distance statistics', *Geographical Analysis,* 24: 189-206.

Giuliano, G. and Small, K. (1991), 'Subcentres in the Los Angeles region', *Regional Science and Urban Economics,* 21: 163-182.

Giuliano, G. and Small, K. (1993), 'Is the journey to work explained by urban structure?' *Urban Studies,* 30(9): 1485-1500.

Glaeser, E., Kallal, H.D., Scheinkman, J.A. and Shleifer, A. (1992), 'Growth in cities', *The Journal of Political Economy,* 100(6): 1126-1152.

Glaeser, E., Kolko, J. and Saiz, A. (2001), 'Consumer city', *Journal of Economic Geography,* 1: 27-50.

Gomez-Ibanez, J. (1991), 'A global view of automobile dependence- review of P Newman and J Kenworthy Cities and automobile dependence: a sourcebook', *Journal of the American Planning Association,* 57: 376-379.

Goodchild, M.F. (2005), 'GIS, spatial analysis, and modelling overview', in Maguire, D.J., Batty, M. and Goodchild, M.F. (eds.), *GIS, Spatial Analysis and Modelling*, ESRI Press, Redlands, CA, pp. 1-18.

Goodwin, P.B. (1992), 'A review of new demand elasticities with special reference to short and long run effects of price changes', *Journal of Transport Economics and Policy,* 26(2): 155-169.

Gordon, I.R. (2008), 'Density and the built environment', *Energy Policy,* 36: 4652-4656.

Gordon, I.R. and McCann, P. (2000), 'Industrial clusters: complexes, agglomerations and/or social networks?' *Urban Studies,* 37(3): 513-532.

Gordon, P., Kumar, A. and Richardson, H.W. (1989), 'The influence of metropolitan spatial structure on commuting time', *Journal of Urban Economics,* 26(2): 138-151.

Gordon, P. and Richardson, H.W. (1996), 'Beyond polycentricity: the dispersed metropolis, Los Angeles, 1970-1990', *Journal of the American Planning Association,* 62(3): 289-295.

Gordon, P., Richardson, H.W. and Jun, M. (1991), 'The commuting paradox: evidence from the top twenty', *Journal of the American Planning Association,* 57(416-420).

Graham, D. (2003), *Industrial concentration and agglomeration in London,* Centre for Transport Studies, Imperial College London, London.

Graham, D. (2005), *Wider economic benefits of transport improvements: link between agglomeration and productivity,* Centre for Transport Studies, Imperial College London, London.

Greater London Authority (2004), *The London Plan: spatial development strategy for Greater London,* The Greater London Authority, London, UK.

Greater London Authority (2007a), *Commuting in London,* GLA, London.

Greater London Authority (2007b), *London office policy review 2006,* Greater London Authority, London.

Greater London Authority (2008), *Historic Census Population [computer file]*, Greater London Authority, London. URL: http://data.london.gov.uk/datastore/package/historic-census-population.

Greater London Authority (2009), *London office policy review 2008,* GLA, London.

Hall, J.W., Dawson, R.J., Barr, S.L., Batty, M., Bristow, A.L., Carney, S., Dagoumas, A., Ford, A.C., Harpham, C., Tight, M.R., Walsh, C.L., Watters, H. and Zanni, A.M. (2010), 'City-scale integrated assessment of climate impacts, adaptation and mitigation', in Bose, R.K. (ed.) *Energy efficient cities: assessment tools and benchmarking practices*, The World Bank, Washington D.C.

Hall, P. (1998a), *Cities in civilization,* Pantheon, New York.

Hall, P. (1998b), *Cities of tomorrow,* Oxford, London.

Hall, P. (1999), 'The future of cities', *Computers, Environment and Urban Systems,* 23: 173-185.

Hall, P. and Pain, K. (2006), *The polycentric metropolis: learning from mega-city regions in Europe,* Earthscan, London.

Hamilton, F.E.I. (1984), 'Industrial restructuring: an international problem', *Geoforum,* 15: 349-64.

Handy, S. (1993), 'Regional versus local accessibility: implications for non-work travel', *Transportation Research Record,* 1400: 58-66.

Handy, S. (1995), 'Urban form and pedestrian choices: study of Austin neighbourhoods', *Transportation Research Record,* 1400: 135-144.

Handy, S. (1996), 'Travel behaviour issues related to neo-traditional developments- a review of the research', *TMIP Conference on Urban Design, Telecommuting and Travel Behaviour*, Federal Highway Administration, Washington, D.C.

Handy, S. and Niemeier, D.A. (1997), 'Measuring accessibility: an exploration of issues and alternatives', *Environment and Planning A,* 29: 1175-1194.

Hansen, W.G. (1959), 'How accessibility shapes land use', *Journal of the American Institute of Planners,* 25: 73-76.

Harris, C.D. and Ullman, E.L. (1945), 'The nature of cities', *Annals, American Academy of Political and Social Sciences,* 242: 7-17.

Hart, P.E., Nilsson, N.J. and Raphael, B. (1968), 'A formal basis for the heuristic determination of mimimum cost paths', *Systems Science and Cybernetics, IEEE Transactions on,* 4(2): 100-107.

Harvey, D. (1978), 'The urban process under capitalism', *International Journal of Urban and Regional Research,* 2(1): 101-31.

Harvey, D. (2001), 'Globalization and the "spatial fix"', *Geographische Revue,* 2: 23-30.

Henderson, V., Kuncoro, A. and Turner, M. (1995), 'Industrial development in cities', *The Journal of Political Economy,* 103(5): 1067-1090.

Hickman, R., Ashiru, O. and Banister, D. (2010), 'Transport and climate change: simulating the options for carbon reduction in London', *Transport Policy,* 17(2): 110-125.

Hillier, B. (1996), 'Cities as movement economies', *Urban Design International,* 1(1): 41-60.

Hirsch, R.L. (2007), *Peaking of world oil production: recent forecasts,* United States Department of Energy, Washington D. C.

Hoover, E.M. (1948), *The location of economic activity,* McGraw-Hill, New York.

Horner, M. (2004), 'Spatial dimensions of urban commuting: a review of major issues and their implications for future geographical research', *The Professional Geographer,* 56(2): 160-173.

Houghton, J.T., Jenkins, G.J. and Ephraums, J.J. (eds.) **(1990)**, *Climate change 1992: the supplementary report to the IPCC scientific assessment,* Cambridge University Press, Cambridge.

Hugill, P. (1993), *World trade since 1941. Geography, technology and capitalism.,* John Hopkins University Press, Baltimore.

Hupkes, G. (1982), 'The law of constant travel time and trip-rates', *Futures,* 14: 38-46.

Intergovernmental Panel on Climate Change (2007), *Climate change 2007: synthesis report,* IPCC, Geneva, Switzerland.

International Energy Agency (2008), *World Energy Outlook 2008,* OECD, Paris.

International Union for the Conservation of Nature and Natural Resources (1980), *World conservation strategy: living resource conservation for sustainable development,* IUCN, Gland, Switzerland.

ITIS Holdings (2007), *Weekday network speed data produced by the TfL Road Network Performance Team*, ITIS Holdings, Antrincham, Cheshire.

Jacobs, J. (1961), *The death and life of great American cities,* Vintage Books, New York, NY.

Jacobs, J. (1969), *The economy of cities,* Vintage, New York.

Jenks, M., Burton, E. and Williams, K. (eds.) **(1996)**, *The compact city: a sustainable urban form? ,* E&FN Spon, London.

Johnston, R.J., Gregory, D., Pratt, G. and Watts, M. (2000), *The Dictionary of Human Geography (4th Edition),* Blackwell Publishers, Oxford, UK.

Kirwan, R. (1992), 'Urban form, energy and transport: a note on the Newman-Kenworthy thesis', *Urban Policy and Research,* 10(1): pp. 6-23.

Kitamura, R., Mokhtarian, P.L. and Laidet, L. (1997), 'A micro-analysis of land use and travel in five neighborhoods in the San Francisco bay area', *Transportation 24*: 125-158.

Klein, R.J.T., Nicholls, R.J. and Thomalla, F. (2003), 'The resilience of coastal megacities to weather-related hazards: a review', in Kreimer, A., Arnold, M. and Carlin, A. (eds.), *Building safer cities: the future of disaster risk*, World Bank, Washington, DC, pp. 101-120.

Knox, P., Agnew, J. and McCarthy, L. (2003), *The geography of the world economy,* Arnold, London.

Kondratieff, N.D. (1935), 'The long waves in economic life', *Review of Economics and Statistics,* 17: 105-115.

Kronmal, R. (1993), 'Correlation and the Fallacy of the Ratio Standard Revisited', *Journal of the Royal Statistical Society Series A*, 156(3): 379-392.

Lash, S. and Urry, J. (1987), *The end of organised capitalism,* Polity Press, Cambridge.

Lele, S.M. (1991), 'Sustainable development: a critical review', *World Development,* 19(6): 607-621.

Levinson, D. (2008), 'Density and dispersion: the co-development of land use and rail in London', *Journal of Economic Geography,* 8: 55-77.

Longley, P.A. and Batty, M. (1996), 'Spatial analysis: modelling in a GIS environment', Geoinformation International, Cambridge, UK.

Longley, P.A., Brooks, S.M., McDonnell, R. and Macmillan, B. (eds.) **(1998)**, *Geocomputation: a primer,* John Wiley & Sons, Chichester, UK.

Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (2005), *Geographical Information Systems and science (2nd Edition),* John Wiley & Sons, New York, NY.

Longley, P.A. and Mesev, T.V. (2000), 'On the measurement and generalisation of urban form', *Environment and Planning A,* 32(3): 473-488.

Lovelock, J. (1979), *Gaia,* Oxford University Press, Oxford, UK.

Ma, K. and Banister, D. (2007), 'Urban spatial change and excess commuting', *Environment and Planning A,* 39(3): 630-646.

Maguire, S., Tewdwr-Jones, M. and Edwards, M. (2004), *Intra-urban polycentric development: suburban trajectories,* Office of the Deputy Prime Minister, London.

Malmberg, A. and Maskell, P. (2002), 'The elusive concept of localization economies: towards a knoledge-based theory of spatial clustering', *Environment and Planning A,* 34(3): 429-449.

Marshall, A. (1890), *Principles of economics,* McMillan, London.

Martin, D. (2002), 'Geography for the 2001 census in England and Wales', *Population Trends,* 108: 7-15.

McLoughlin, J.B. (1969), *Urban and regional planning: a systems approach,* Faber & Faber, London.

Meadows, D.H. and Meadows, D.L. (1972), *The limits of growth,* New American Library, New York.

Meijers, E. (2007), *Synergy in polycentric urban regions: complementarity, organising capacity and critical mass,* Delft University of Technology, Amsterdam.

Mellart, J. (1967), *Catal Huyuk,* McGraw-Hill, New York.

Menard, S. (1995), *Applied logistic regression analysis: sage university series on quantitative applications in the social sciences,* Sage, Thousand Oaks, CA.

Metschies, G.P. (2005), *International fuel prices 2005,* Deutsche Gesellschaft fur Technische, Zusammenarbeit, Eschborn.

Mindali, O., Raveh, A. and Salomon, I. (2004), 'Urban density and energy consumption: a new look at old statistics', *Transportation Research Part A,* 38: 143-162.

Ministry of Health (1944), *The housing manual,* HMSO, London.

Mokhtarian, P.L. and Salomon, I. (2001), 'How derived is the demand for travel? Some conceptual and measurement considerations', *Transportation Research Part A,* 35(8): 695-719.

Monmonier, M. (1991), *How to lie with maps,* University of Chicago Press, Chicago.

Monzon, A. and Nuijten, A. (eds.) **(2006)**, *STEPs final report: transport strategies under the scarcity of energy supply,* Buck Consultants International, The Hague.

Muller, P.O. (ed.) **(2004)**, *Stages in the spatial evolution of the American metropolis (3rd)*.

Murphy, R.E. and Vance, J.E. (1954), 'Delimiting the CBD', *Economic Geography,* 30(3): 189-222.

Nachum, L. and Keeble, D. (2003), 'Neo-Marshallian clusters and global networks', *Long Range Planning,* 36: 459-480.

National Public Transport Data Repository (2010), *UK public transport timetable October 2010*, Department for Transport, London. URL: http://data.gov.uk/dataset/nptdr.

Newman, P. and Kenworthy, J. (1989), *Cities and automobile dependence: an international sourcebook,* Gower, Aldershot, England.

Newman, P. and Kenworthy, J. (1999), *Sustainability and cities: overcoming automobile dependence,* Island Press, Washington, DC.

Nexus Research Group (2010), *London Underground and National Rail 1801-2008*, University of Minnesota, Minneapolis, MN. URL: http://nexus.umn.edu/movies.html.

Office for National Statistics (2004), *Model-based estimates of income for wards in England and Wales 2001/02,* Office for National Statistics, London.

Office for National Statistics (2010a), *2001 Census: Standard Area Statistics (England and Wales) [computer file]*, ESRC/JISC Census Programme, Census Dissemination Unit, Mimas (University of Manchester). URL: http://cdu.mimas.ac.uk.

Office for National Statistics (2010b), *2001 Census: Special Workplace Statistics (England, Wales and Northern Ireland) [computer file]*, ESRC/JISC Census Programme, Centre for Interaction Data Estimation and Research (University of Leeds). URL: http://cids.census.ac.uk.

Office for National Statistics (2010c), *Annual Business Index 1998-2008 [computer file]*, Nomis Official Labour Market Statistics. URL: http://www.nomisweb.co.uk.

Office of the Deputy Prime Minister (2005), *Planning Policy Statement 1: delivering sustainable development,* ODPM, Norwich, UK.

Openshaw, S. (1984), *The Modifiable Areal Unit Problem,* Geo-Books, Norwich, UK.

Openshaw, S. (1996), 'Developing GIS-relevant zone-based spatial analysis methods', in Longley, P.A. and Batty, M. (eds.), *Spatial analysis: modelling in a GIS environment*, Geoinformation International, London.

Ordnance Survey (2007a), *OS MasterMap Topography Layer [GML geospatial data]*, EDINA Digimap Ordnance Survey Service (University of Edinburgh). URL: http://edina.ac.uk/digimap.

Ordnance Survey (2007b), *OS MasterMap ITN Layer [GML geospatial data]*, EDINA Digimap Ordnance Survey Service (University of Edinburgh). URL: http://edina.ac.uk/digimap.

Ordnance Survey (2007c), *OS Meridian 2 [geospatial data]*, EDINA Digimap Ordnance Survey Service (University of Edinburgh). URL: http://edina.ac.uk/digimap.

Orford, S. and Ratcliffe, J. (2007), 'Modelling UK residential dwelling types using OS Mastermap data: a comparison to the 2001 Census', *Computers, Environment and Urban Systems,* 30(2): 206–227.

Pacione, M. (2009), *Urban geography: a global perspective,* Routledge, London.

Parr, J. (2004), 'The Polycentric Urban Region: a closer inspection', *Regional Studies,* 38(3): 231-240.

Perez, C. (2002), *Technological revolutions and financial capital: the dynamics of bubbles and golden ages,* Edward Elgar, Cheltnam, UK.

Plane, D. (1995), 'Urban transportation : policy alternatives', in Hanson, S. (ed.) *The geography of travel*, Guilford Press, New York.

Pollard, S. (1981), *Peaceful conquest: the industrialization of Europe, 1760-1970,* Oxford University Press, Oxford.

Pont, M.B. and Haupt, P. (2007), 'The relation between urban form and density', *Urban Morphology,* 11(1): 62-66.

Porter, M.E. (2000), 'Location, competition and economic development: local clusters in a global economy', *Economic Development Quarterly,* 14(1): 15-34.

Pucher, J. (ed.) **(2003)**, *Public transportation,* Guildford Press, New York.

Raper, J. (2000), *Multidimensional geographical information science,* Taylor and Francis, London.

Ravetz, J. (2000), 'Integrated assessment for sustainability appraisal in cities and regions', *Environmental Impact Assessment Review,* 20: 31-64.

Reades, J., Calabrese, F. and Ratti, C. (2007), 'Cellular census: explorations in urban data collection', *Pervasive Computing,* 6(3): 30-38.

Redfearn, C.L. (2007), 'The topography of metropolitan employment: identifying centers of employment in a polycentric urban area', *Journal of Urban Economics,* 61: 519-541.

Rees, W.E. (1992), 'Ecological footprints and appropriated carrying capacity: what urban economics leaves out', *Environment and Urbanization,* 4(2): 121-130.

Sassen, S. (1991), *The global city,* Princeton University Press, Princeton, N.J.

Schumpeter, J. (1939), *Business cycles: a theoretical historical and statistical analysis of the capitalist process,* McGraw-Hill, New York.

Scott, A.J. (1988), *Metropolis: from the division of labour to urban form,* University of California Press, Berkeley.

Scott, A.J. (1996), 'Regional motors of the global economy', *Futures,* 28: 391-411.

Sherlock, H. (1991), *Cities are good for us,* Paladin, London.

Skupin, A. (2000), 'From metaphor to method: cartographic perspectives on information visualization', *Proceedings IEEE Symposium on Information Visualization (InfoVis 2000)*, 9th -10th October, Salt Lake City, UT.

Smith, D.M. (1966), 'A theoretical framework for geographical studies of industrial location', *Economic Geography,* 42(2): 95-113.

Soja, E.W. (2000), *Postmetropolis: critical studies of cities and regions,* Blackwell, Oxford, UK.

Soule, M.E. and Wilcox, B.A. (eds.) **(1980)**, *Conservation biology: an evolutionary-ecological perspective,* Sinauer, Sunderland, MA.

Stead, D. (2001), 'Relationships between land use, socioeconomic factors, and travel patterns in Britain', *Environment and Planning B: Planning and Design,* 28: 499-528.

Stiglitz, J. (2010), *Freefall,* Penguin, London.

Storper, M. and Venables, A.J. (2004), 'Buzz: face-to-face contact and the urban economy', *Journal of Economic Geography,* 4: 351-370.

Sudjic, D. (1995), *The 100 mile city,* Flamingo, London.

Talen, E. (2003), 'Measuring urbanism: issues in Smart Growth research', *Journal of Urban Design,* 8(3): 195-215.

Thomas, R. (1969), *London's New Towns: a study of self-contained and balanced communities,* PEP, London.

Thomson, J.M. (1977), *Great cities and their traffic,* Victor Gollancz, London.

Thrift, N. (2002), 'A hyperactive word', in Johnston, R.J., Taylor, P.J. and Watts, M. (eds.), *Geographies of global change: remapping the world (2nd)*, Blackwell, Oxford, pp. 18-35.

Thünen, J.H., von. (1826), *Der isolierte staat in beziehung auf landwirtschaft und nationalokonomie,* Gustav Fisher, Stuttgart, Germany.

Thurstain-Goodwin, M. and Unwin, D. (2000), *Defining and delineating the central areas of towns for statistical monitoring using continuous surface representations,* Centre for Advanced Spatial Analysis Working Paper, University College London, London.

Tickell, A. and Peck, J.A. (1992), 'Accumulation, regulation and the geographies of post-Fordism: missing links in regulationist research', *Progress in Human Geography,* 16(2): 190-218.

Titheridge, H. and Hall, P. (2006), 'Changing travel to work patterns in South East England', *Journal of Transport Geography,* 14: 60-75.

Tobler, W. (1970), 'A computer movie simulating urban growth in the Detroit region', *Economic Geography,* 46: 234-40.

Tolley, R.S. and Turton, B.J. (1995), *Transport systems, policy and planning: a geographical approach,* Longman, Harlow, Essex.

Tomlin, D.C. (1990), *Geographic Information Systems and cartographic modelling,* Prentice-Hall, Englewood Cliffs, N.J.

Transport for London (2005), *Road network performance team technical note 1: ITIS speed survey data,* TfL, London.

Transport for London (2010), *Travel in London Report 3*, TfL, London.

Turvey, R. (2005), 'Horse traction in Victorian London', *Journal of Transport History,* 28(2): 38-59.

UNFPA (2007), *State of world population 2007,* United Nations Population Fund, New York.

Unwin, R. (1912), *Nothing gained by overcrowding! ,* P.S. King, London.

Urban Task Force (1999), *Towards an Urban Renaissance,* Department for Environment Transport and the Regions, London.

van Oosterom, P., Zlatanova, S., Penninga, F. and Fendel, E. (eds.) **(2008)**, *Advances in 3D geoinformation systems,* Springer-Verlag, Berlin.

Valuation Office Agency (2005), *Non-Domestic Rates Listing [computer file]*, Valuation Office Agency, London.

Wallerstein, I. (1979), *The capitalist world economy,* Cambridge University Press, New York.

Wang, F. (2000), 'Modeling commuting patterns in Chicago in a GIS environment: a job accessiblity perspective', *The Professional Geographer,* 52(1): 120-133.

Weber, A. (1909), *The theory of the location of industries,* JCB Mohr, Tübingen.

Wegener, M. (1994), 'Operational urban models: state of the art', *Journal of the American Planning Association,* 60(1): 17-29.

Wegener, M. (2004), 'Overview of land use transport models', in Hensher, D.A. (ed.) *Handbook of transport geography and spatial systems*, Elsevier, Oxford.

Wharf, B. (1995), 'Telecommunications and the changing geographies of knowledge transmission in the late 20th century', *Urban Studies,* 32(2): 361-378.

Williams, I.N. and Echenique, M.H. (1978), 'A regional model for commodity and passenger flow', *PTRC Summer Annual Meeting*, PTRC, London.

Wood, P. (2002), 'Knowledge intensive services and urban innovativeness ', *Urban Studies,* 39(5-6): 993-1002.

World Commission on Environment and Development (1987), *Our common future,* Oxford University Press, New York.

Zahavi, Y. and Talvitie, A. (1980), 'Regularities in travel time and money expenditures', *Transportation Research Record,* 750: 13-19.

Appendix A: World Cities Urban Form and Travel Sustainability Dataset

The international cities comparison analysis in Sub-Section 3.3.3 is uses the Newman and Kenworthy (1999) dataset. This is presented in full in Table A1. Note that not all the cities in Table A1 are included in the Sub-Section 3.3.3 analysis due to the high levels of income and density variation, as detailed on page 78.

City	Private Transport (km per capita)	Public Transport (km per capita)	Private Transport Energy Use (MJ per capita)	Public Transport Energy Use (MJ per capita)	Total Energy Use (MJ per capita)	Transport Energy / $ GRP (MJ/$)	Total Passenger km on Transit (%)	Transit Service Level (service km per capita)	Road Supply (metres per capita)	Car Average Speed (km)	Train Average Speed (km)	Bus Average Speed (km)	Metropolitan Population Density (residents /hectare)	Metropolitan Employ. Density (jobs/hectare)
Houston	19,004	215	71,125	499	71,624	2.74	1.10	16.70	11.70	61.20		23.60	9.50	5.70
Phoenix	15,903	124	64,339	301	64,640	3.14	0.80	9.90	9.60	51.50		24.50	10.50	5.10
San Francisco	16,229	899	64,680	1,210	65,890	2.12	5.30	49.30	4.60	44.30	43.30	20.10	16.00	8.50
Denver	13,515	199	67,692	594	68,286	2.78	1.40	21.20	7.60	58.10		24.20	12.80	8.70
Los Angeles	16,686	352	61,525	643	62,168	2.50	2.10	19.80	3.80	45.00		19.90	23.90	12.40
Detroit	15,846	171	62,339	405	62,744	2.78	1.10	14.00	6.00	56.30		22.50	12.80	6.10
Boston	17,373	627	57,293	1,097	58,390	2.10	3.50	36.00	6.70	52.30	32.60	20.10	12.00	7.10
Washington	16,214	774	59,325	1,129	60,454	1.68	4.60	37.30	5.20	42.40	39.40	19.30	13.70	9.50
Chicago	14,096	805	54,853	1,268	56,121	2.16	5.40	41.50	5.20	45.00	46.10	17.90	16.60	8.70
New York	11,062	1,334	50,156	1,469	51,625	1.80	10.80	62.80	4.60	38.30	39.00	18.80	19.20	11.00
Perth	12,029	544	40,544	851	41,395	2.34	4.30	47.00	10.70	45.00	34.00	24.60	10.60	4.40
Brisbane	11,188	900	38,361	916	39,277	2.10	7.40	55.10	8.20	50.10	44.00	28.70	9.80	4.00
Melbourne	9,782	844	38,140	749	38,889	1.84	7.90	49.90	7.70	45.10	28.60	21.00	14.90	5.90
Adelaide	11,173	572	36,143	959	37,102	1.88	4.90	46.40	8.00	46.40	26.30	22.10	11.80	5.10
Sydney	9,417	1,769	33,972	1,102	35,074	1.63	15.80	94.00	6.20	37.00	42.00	19.00	16.80	7.20
Toronto	7,027	2,173	31,804	1,809	33,613	1.49	23.60	98.40	2.60	35.00	30.90	20.30	41.50	23.20

Table A1: Travel patterns, transportation energy use, infrastructure, income and urban form data for a selection of world cities (Newman and Kenworthy, 1999)

City	Private Transport (km per capita)	Public Transport (km per capita)	Private Transport Energy Use (MJ per capita)	Public Transport Energy Use (MJ per capita)	Total Energy Use (MJ per capita)	Transport Energy / $ GRP (MJ/$)	Total Passenger km on Transit (%)	Transit Service Level (service km per capita)	Road Supply (metres per capita)	Car Average Speed (km)	Train Average Speed (km)	Bus Average Speed (km)	Metropolitan Population Density (residents /hectare)	Metropolitan Employ. Density (jobs/hectare)
Frankfurt	8,309	1,149	37,550	742	38,292	1.09	12.10	47.90	2.00	45.00	46.80	19.60	46.60	43.30
Brussels	6,809	1,428	27,377	1,518	28,895	0.96	17.30	62.70	2.10	37.90	31.80	19.10	74.90	46.80
Hamburg	7,592	1,375	35,807	908	36,715	1.21	15.30	71.00	2.60	30.00	37.30	22.00	39.80	23.60
Zurich	7,692	2,459	23,822	1,422	25,244	0.56	24.20	148.10	4.00	36.00	45.20	21.10	47.10	35.20
Stockholm	6,261	2,351	24,998	1,819	26,817	0.81	27.30	133.20	2.20	43.00	43.90	27.20	53.10	39.30
Vienna	5,272	2,430	19,377	1,227	20,604	0.74	31.60	72.60	1.80	27.50	26.50	19.10	68.30	37.40
Copenhagen	7,749	1,607	18,700	1,685	20,385	0.68	17.20	121.30	4.60	50.00	59.20	24.20	28.60	16.00
Paris	4,842	2,121	23,295	1,269	24,564	0.72	30.50	71.00	0.90	25.70	41.80	23.20	46.10	22.10
Munich	5,925	2,463	16,822	1,376	18,198	0.50	29.40	91.40	1.80	35.00	46.20	23.20	53.60	37.20
Amsterdam	6,522	1,061	19,011	831	19,842	0.79	14.00	60.30	2.60	35.00	25.00	16.30	48.80	22.20
London	5,644	2,405	22,024	1,350	23,374	1.05	29.90	138.40	2.00	30.20	48.30	19.00	42.30	23.60
Kuala Lumpur	6,299	1,577	19,243	774	20,017	4.92	20.00	49.70	1.50	29.40		16.30	58.70	22.40
Singapore	3,169	2,775	16,340	1,739	18,079	1.40	46.70	114.00	1.10	32.50	40.00	19.20	86.80	49.30
Tokyo	3,175	5,501	17,320	923	18,243	0.49	63.40	89.30	3.90	24.40	39.60	12.00	71.00	73.10
Bangkok	4,634	2,313	15,151	3,026	18,177	4.75	33.30	110.30	0.60	13.10	34.00	9.00	149.30	62.40
Seoul	2,464	2,890	7,897	1,719	9,616	1.62	54.00	113.90	0.80	24.00	39.80	18.80	244.80	101.60
Jakarta	1,546	1,323	8,632	440	9,072	6.02	46.10	54.50	0.50	23.60	35.60	14.60	170.80	58.80
Manila	1,281	2,568	5,630	1,706	7,336	6.67	66.70	257.90	0.60	25.50	37.50	15.40	198.00	67.70
Subaraya	1,568	555	5,317	294	5,611	7.73	26.10	62.20	0.30	27.00		17.50	176.90	77.90
Hong Kong	813	3,784	8,085	1,527	9,612	0.68	82.30	140.40	0.30	25.70	40.20	18.40	300.50	140.00

Table A1 (cont.): Travel patterns, transportation energy use, infrastructure, income and urban form data for a selection of world cities (Newman and Kenworthy, 1999)

Appendix B: London Sectoral Specialisation 4 Digit SIC

The analysis of sectoral specialisation in London is presented at 2 digit SIC level in Sub-Section 5.2.1. The equivalent tables at the more detailed 4 digit SIC level are presented here. As business dynamics are often narrowly focussed within sectors, more extreme patterns of growth and decline can be identified at the 4-digit level sectoral level.

Table B.1: London highest sector concentrations 4 digit SIC level 1998-2002 average.
Data Source: Annual Business Index 1998-2002 (ONS, 2010c).

SIC	Industry	London Total	London Loc. Quotient	Greater South East LQ
6511	Central banking	1,629	5.59	1.71
9240	News agency activities	74,96	4.99	1.73
6711	Administration of financial markets	2,206	4.69	1.74
6712	Security broking and fund management	35,843	4.29	1.58
2214	Publishing of sound recordings	1,834	4.25	1.77
2232	Reproduction of video recording	1,495	4.24	1.79
6523	Other financial intermediation	30,479	4.17	1.60
9211	Motion picture and video production	9,699	3.91	1.64
9212	Motion picture and video distribution	3,266	3.87	1.47
9220	Radio and television activities	36,500	3.46	1.37
9112	Activities of professional organisations	7,798	3.12	1.46
6210	Scheduled air transport	35,232	3.03	1.74
2213	Publishing of journals and periodicals	26,215	2.95	1.48
6713	Activities auxiliary to financial intermediation	19,679	2.94	1.52
2221	Printing of newspapers	2,875	2.78	1.30
9231	Artistic and literary	27,948	2.76	1.39
2211	Publishing of books	13,702	2.76	1.58
7012	Buying and selling of own real-estate	1,960	2.70	1.40
9111	Business and employers organisations	5,008	2.66	1.39
7440	Advertising	35,688	2.61	1.46
9232	Operation of arts facilities	5,331	2.57	1.38
7413	Market research, public opinion	15,679	2.48	1.48
5145	Wholesale of perfume and cosmetics	5,052	2.35	1.55
9120	Activities of trade unions	4,450	2.32	1.22
2231	Reproduction of sound recording	1,654	2.32	1.17
6010	Transport via railways	16,710	2.17	1.13
2464	Manufacture photographic chemical material	1,891	2.16	1.14
7240	Data base activities	3,131	2.16	1.39
7411	Legal activities	82,190	2.15	1.16
6321	Other supporting land transport activities	10,754	2.15	1.19
7032	Management of real-estate	14,260	2.06	1.40
5142	Wholesale of clothing and footwear	12,302	2.03	1.07
5116	Sale of textiles, clothing agents	1,606	2.03	1.10
9213	Motion picture projection	4,839	2.03	1.25
7414	Business and management consultancy	61,935	2.01	1.41

Table B.2: London growing sectors 4 digit SIC level 2000-2007
Data Source: Annual Business Index 1998-2002, 2006-2008 (ONS, 2010c).

SIC	Industry	London Total 2000	London Total 2007	Employ. Change	Loc. Quot. 2007
7414	Business and mng. consultancy	61,935	95,968	34,033	1.90
8511	Hospital activities	148,574	173,150	24,576	0.76
8010	Primary education	94,622	119,190	24,568	0.74
8514	Other human health activities	22,232	42,183	19,950	0.85
5530	Restaurants	116,868	135,864	18,996	1.36
7470	Industrial cleaning	87,915	106,829	18,915	1.51
8532	Social work activities	77,174	93,069	15,895	0.87
6321	Other supporting land transport	10,754	25,205	14,451	2.25
5242	Retail sale of clothing	54,547	68,389	13,842	1.19
6712	Security broking and fund mng	35,843	48,178	12,334	4.73
7032	Management of real-estate	14,260	25,763	11,503	1.52
7524	Public security, law and order	46,006	56,551	10,545	1.30
7413	Market research, opinion polling	15,679	26,071	10,392	2.80
7511	General public service activities	83,893	93,751	9,858	0.97
7460	Investigation and security activities	35,307	44,819	9,512	1.69
6210	Scheduled air transport	35,232	44,658	9,426	3.91
6713	Aux. to financial intermediation	19,679	28,024	8,345	2.20
7411	Legal activities	82,190	89,981	7,791	2.00
6523	Other financial intermediation	30,479	37,924	7,445	4.21
8042	Adult and other education	25,352	31,825	6,473	0.95
7420	Architectural and engineering	57,881	64,275	6,393	1.11
5248	Other retail sale	46,464	52,593	6,130	0.91
8022	Technical secondary education	13,579	18,904	5,325	0.84
5552	Catering	45,152	50,456	5,304	1.43
7450	Labour recruitment	158,587	163,751	5,164	1.30

Table B.3: London declining sectors 4 digit SIC level 2000-2007
Data Source: Annual Business Index 1998-2002, 2006-2008 (ONS, 2010c).

SIC	Industry	London Total 2000	London Total 2007	Employ. Change	Loc. Quot. 2007
6512	Other monetary intermediation	155,133	135,596	-19,537	1.83
4521	General construction	64,702	48,424	-16,278	0.64
5212	Other retail sale in non-specialised stores	48,830	37,839	-10,991	1.07
6411	National post activities	41,110	30,788	-10,323	1.03
6420	Telecommunications	54,154	44,212	-9,942	1.37
6330	Activities of travel agencies	32,941	24,370	-8,571	1.52
2222	Printing not elsewhere classified	23,146	14,881	-8,265	0.84
6601	Life insurance	14,528	6,387	-8,141	0.61
7260	Other computer related activities	27,893	20,118	-7,775	1.4
5010	Sale of motor vehicles	20,355	14,121	-6,234	0.42
5190	Other wholesale	18,683	12,561	-6,122	0.95
7230	Data processing	11,151	5,256	-5,894	1.01
7011	Development and selling of real-estate	21,465	16,185	-5,280	1.35

Appendix C: Employment Centres Sectoral Specialisation

The analysis of the geography of sectoral specialisation in Sub-Section 5.2.5 focussed on the most prominent agglomerations in Central London, West London and the Western Sector. The tables here provide a more comprehensive dataset of sectoral specialisation for all the employment centres in the study area.

Table C.1: Central and Inner London Employment Centre Sectoral Specialisation
Data Source: Annual Business Index 1998-2002 (ONS, 2010c).

Centre Name	Employment (2001 Census)	Population (2001 Census)	Sectoral Specialisations (4 Digit SIC's with Location Quotient Greater than 2)	
City of London	311,825	7,185	Central_banking6511 16.89; FinanceMarketAdmin6711 8.45; BrokingFundManange6712 8.31; InsuranceAuxil6720 6.58; LegalActivities7411 6.37; OtherFinancialInter6523 6.27;	OtherMonetaryInter6512 5.72; NonLifeInsurance6603 5.31; LifeInsurance6601 4.36; Accountancy7412 3.53; FinancialInterAuxil6713 3.16; TechnicalTesting7430 3.10;
West End	239,498	25,547	MotionPicutreVidProduc9211 7.16; MotionPicutreVidDistr9212 6.13; OwnRealEstateBuySell7012 4.17; Advertising7440 4.03; SoundPublish2214 3.26; RadioTelevisionActiv9220 2.90; Hotels5510 2.81; JournalsPublish2213 2.79; RealEstateManage7032 2.77; RealEstateAgencies7031 2.61; RetailClothing5242 2.59;	RealEstateDevSell7011 2.57; RetailSecondHand5250 2.54; HigherEducation8030 2.42; RetailOtherNonspecial5212 2.40; OtherEntertainment9234 2.35; MusuemHistoricBuildings9252 2.33; RetailFootwearLeather5243 2.20; ArtsFacilitiesOperation9232 2.16; LettingOwnProp7020 2.10; ArchitectureEngineering7420 2.02; SoundReproduction2231 2.01;
City Fringe	237,964	121,124	NewsAgencyActivities9240 8.15; NewsPublish2212 7.32; MarketResearch7413 4.30; OtherLandTransport6321 3.90; DatabaseActivities7240 3.89; Telecommunications6420 3.86; PrintingAncillary2225 3.51; JournalsPublish2213 3.47; PrepressActivities2224 3.30;	RandDSocSci7320 3.17; CallCentreActivities7486 3.06; Accountancy7412 2.65; MusuemHistoricBuildings9252 2.27; PhotographicActivities7481 2.23; ArtsFacilitiesOperation9232 2.11; BrokingFundManange6712 2.03; PublicServiceRegulation7512 2.01;
Whitehall	195,534	17,288	ForeignAffairs7521 28.19; DefenceActivities7522 9.00; ArtsFacilitiesOperation9232 5.60; SecretarialTranslationServ7485 5.24; MusuemHistoricBuildings9252 5.09; JusticeJudicialActivities7523 4.50; PublicServiceGeneral7511 4.30; RetailTextiles5241 3.55; SocialServiceCompuls7530 3.53;	PublicServiceRegulation7512 3.51; BookPublish2211 3.30; RadioTelevisionActiv9220 2.89; ArtisticLiteraryActivitie9231 2.77; PublicSecurityLawOrder7524 2.75; ManagementHoldingComp7415 2.37; RandDSocSci7320 2.36; MotionPictureProjection9213 2.36; Accountancy7412 2.05;
West Central	116,551	31,831	LegalActivities7411 5.44; OtherLandTransport6321 4.59; NewsPublish2212 4.51; BusinessRegulation7513 4.08; OtherPublish2215 3.67; NewsAgencyActivities9240 3.65; JournalsPublish2213 3.56; MotionPicutreVidDistr9212 3.34; BookPublish2211 3.29; RepairWatchesJewel5273 3.23;	DefenceActivities7522 2.93; InvestigationSecurity7460 2.90; Advertising7440 2.89; JusticeJudicialActivities7523 2.73; CompMediaReproduction2233 2.50; FinancialInterAuxil6713 2.46; ArtsFacilitiesOperation9232 2.35; DatabaseActivities7240 2.35; TechnicalTesting7430 2.29; OtherWaterTransport6322 2.24;
Camden Islington	72,383	79,300	OtherLandTransport6321 12.61; BookPublish2211 7.60; LibraryArchive9251 6.36; PrepressActivities2224 6.30; NewsAgencyActivities9240 5.63; FinancialLeasing6521 4.20; OtherPublish2215 3.23; Advertising7440 2.89; PublicServiceGeneral7511 2.45;	MotionPicutreVidProduc9211 2.43; JusticeJudicialActivities7523 2.38; RadioTelevisionActiv9220 2.34; JournalsPublish2213 2.20; ArchitectureEngineering7420 2.19; PrintingAncillary2225 2.14; ArtsFacilitiesOperation9232 2.11; ManagementHoldingComp7415 2.10; PhotographicActivities7481 2.06;

Kensington	70,502	54,372	MusuemHistoricBuildings9252 13.30; NewsPublish2212 10.12; Hotels5510 6.54; ArtsFacilitiesOperation9232 4.89; RetailOtherNonspecial5212 4.80; FinanceMarketAdmin6711 3.47; HigherEducation8030 3.32;	RealEstateAgencies7031 2.72; RetailTextiles5241 2.58; RetailClothing5242 2.44; RetailSecondHand5250 2.21; RetailFootwearLeather5243 2.21; Restaurants5530 2.11; GamblingActivities9271 2.06;
Canary Wharf	65,378	37,315	OtherFinancialInter6523 21.73; FinancialInterAuxil6713 14.27; NewsPrinting2221 13.51; NewsPublish2212 12.62; NewsAgencyActivities9240 10.49; BrokingFundManange6712 8.36;	OtherMonetaryInter6512 6.38; RetailOtherNonStore5263 5.73; FinanceMarketAdmin6711 3.27; RetailSeaFood5223 3.27; BookPublish2211 2.90; SecretarialTranslationServ7485 2.55;
Hammersmith	48,032	54,713	MotionPicutreVidDistr9212 29.31; RadioTelevisionActiv9220 17.67; BookPublish2211 4.12; HardwareConsult7210 4.02; SoundPublish2214 3.88; PrepressActivities2224 3.76; GamblingActivities9271 3.10; JournalsPublish2213 2.76;	TravelAgenciestTours6330 2.56; Advertising7440 2.54; OtherPublish2215 2.44; CompMediaReproduction2233 2.24; RetailMailOrder5261 2.24; LettingOwnProp7020 2.11; SoundReproduction2231 2.11;

Table C.2: Outer London Employment Centre Sectoral Specialisation
Data Source: Annual Business Index 1998-2002 (ONS, 2010c).

Centre Name	Employment (2001 Census)	Population (2001 Census)	Sectoral Specialisations (4 Digit SIC's with Location Quotient Greater than 2)	
Heathrow Fringe	69,745	127,013	CargoHandling6311 20.35; OtherTransportAgencies6340 14.58; DataProcessing7230 11.90; OtherAirTransport6323 8.81; ITMaintenance7250 6.81; JusticeJudicialActivities7523 6.63; DefenceActivities7522 6.17; CompMediaReproduction2233 6.10; ScheduledAirTransport6210 4.51;	HardwareConsult7210 3.14; RetailChemists5231 3.07; SoundReproduction2231 2.75; AdultOtherEducation8042 2.60; OtherSoftwareConsult7222 2.50; StorageWarehousing6312 2.44; MotionPictureProjection9213 2.13; UndertakersFuneral9303 2.03;
Heathrow	69,111	10,217	ScheduledAirTransport6210 50.12; OtherAirTransport6323 34.18; CargoHandling6311 20.68; ComputerManufacture3002 8.10; NonScheduledAirTrans6220 5.89;	OtherTransportAgencies6340 4.02; OtherWaterTransport6322 3.74; InvestigationSecurity7460 3.55; Hotels5510 2.46; RepairShoesLeather5271 2.46;
Croydon	66,721	72,337	NonLifeInsurance6603 6.54; PublicServiceGeneral7511 5.87; RetailFurniture5244 3.92; LifeInsurance6601 2.48; Telecommunications6420 2.34; RetailElectrical5245 2.17; OtherSports9262 2.16;	OtherPublish2215 2.11; LaundryDryClean9301 2.10; OtherLandTransport6321 2.07; RetailSeaFood5223 2.06; RetailOtherNonspecial5212 2.04; Bookbinding2223 2.02;
Western Corridor	50,378	73,026	VideoReproduction2232 18.35; RadioTelevisionActiv9220 12.50; OtherRecreational9272 4.66; CallCentreActivities7486 4.25; PhysicalWellBein9304 3.26; OtherTransportAgencies6340 3.03; MotionPictureProjection9213 2.68;	MotionPicutreVidDistr9212 2.51; ITMaintenance7250 2.31; RetailStallsMarkets5262 2.16; PublicServiceRegulation7512 2.15; ManagementHoldingComp7415 2.11; TechnicalTesting7430 2.09; LabourRecruitment7450 2.00;
Uxbridge	29,516	34,165	LibraryArchive9251 3.92; OtherHumanHealth8514 3.79; PublicServiceRegulation7512 3.59; LabourRecruitment7450 3.22; BusinessRegulation7513 3.04; MotionPictureProjection9213 2.72; InvestigationSecurity7460 2.49;	RetailCosmetics5233 2.45; RandDNaturalSciEng7310 2.35; SecondaryEduTechVoc8022 2.32; RepairElectrical5272 2.32; ManagementHoldingComp7415 2.13; DefenceActivities7522 2.07;
Kingston	28,656	35,956	SoftwarePublish7221 14.21; UndertakersFuneral9303 5.69; RetailOtherNonspecial5212 4.84; BookPublish2211 4.51; RetailClothing5242 3.41; RetailFootwearLeather5243 3.26; HigherEducation8030 2.97; RetailCosmetics5233 2.66;	MotionPictureProjection9213 2.58; OtherPublish2215 2.55; PublicServiceGeneral7511 2.46; RepairShoesLeather5271 2.38; RetailBooksStation5247 2.13; RetailMedical5232 2.06; RetailElectrical5245 2.05;
Harrow	26,851	39,669	MarketResearch7413 6.04; SocialServiceCompuls7530 3.94; RepairWatchesJewel5273 3.54; NewsPrinting2221 2.87; MotionPictureProjection9213 2.73; RetailMedical5232 2.72; OtherRecreational9272 2.66;	HospitalActivities8511 2.59; PublicServiceGeneral7511 2.47; RetailHardware5246 2.42; JusticeJudicialActivities7523 2.36; RetailCosmetics5233 2.09; OtherHumanHealth8514 2.02;

Romford	23,280	26,224	RealEstateManage7032 7.41; SoftwarePublish7221 5.94; InsuranceAuxil6720 4.04; RepairShoesLeather5271 3.34; RetailClothing5242 3.29; SocialServiceCompuls7530 3.28; RetailTextiles5241 3.20; RetailOtherNonspecial5212 3.17; SoundReproduction2231 3.00;	MotionPictureProjection9213 2.94; RetailFootwearLeather5243 2.83; RetailBooksStation5247 2.51; RetailCosmetics5233 2.35; RetailElectrical5245 2.35; SportsArenasOperation9261 2.32; RetailOtherSpecial5248 2.29; LabourRecruitment7450 2.24;
Bromley	21,990	14,499	NonLifeInsurance6603 12.83; TravelAgenciestTours6330 4.16; RetailClothing5242 3.76; PublicServiceRegulation7512 3.20; RetailFootwearLeather5243 3.12; SportsArenasOperation9261 3.05;	RetailOtherNonspecial5212 2.92; PublicServiceGeneral7511 2.59; RetailCosmetics5233 2.54; OtherMonetaryInter6512 2.16; BusinessRegulation7513 2.10;
Enfield	18,602	37,999	MotionPictureProjection9213 5.34; PublicServiceGeneral7511 4.82; RetailHardware5246 3.72; FinancialLeasing6521 3.55; OtherCredit6522 3.49;	RetailElectrical5245 2.95; GovernmentSupport7514 2.69; LabourRecruitment7450 2.68; OtherMonetaryInter6512 2.29; PackagingActivities7482 2.14;
Lewisham	16,120	26,405	GovernmentSupport7514 4.28; FireService7525 3.87; InvestigationSecurity7460 3.72; HospitalActivities8511 3.44; PublicSecurityLawOrder7524 3.32; RetailCosmetics5233 3.19;	GamblingActivities9271 2.57; PublicServiceGeneral7511 2.49; LibraryArchive9251 2.13; RealEstateManage7032 2.07; RetailBooksStation5247 2.01;
Ilford	16,060	36,514	RetailMailOrder5261 7.92; PackagingActivities7482 5.12; InvestigationSecurity7460 3.77; LabourRecruitment7450 3.42; CallCentreActivities7486 3.41; RetailClothing5242 3.16; RetailCosmetics5233 3.14; PublicServiceGeneral7511 3.09; RetailOtherNonspecial5212 2.89;	RetailFruitVeg5221 2.84; LibraryArchive9251 2.80; SocialServiceCompuls7530 2.79; PublicSecurityLawOrder7524 2.78; RetailButchers5222 2.60; RetailFootwearLeather5243 2.51; RetailBooksStation5247 2.32; Telecommunications6420 2.23; NewsPublish2212 2.15;
Ealing	15,920	25,322	MarketResearch7413 8.15; PublicServiceGeneral7511 4.92; BookPublish2211 4.66; InvestigationSecurity7460 2.78;	RetailCosmetics5233 2.57; Restaurants5530 2.53; MotionPicutreVidProduc9211 2.29; RetailSeaFood5223 2.17;
Richmond	15,177	19,868	CallCentreActivities7486 32.05; SecretarialTranslationServ7485 6.06; RealEstateManage7032 5.20; GovernmentSupport7514 3.98; FinancialLeasing6521 3.72; MotionPictureProjection9213 3.69; PublicServiceRegulation7512 3.61; RepairWatchesJewel5273 3.30;	BookPublish2211 2.48; HairdressingBeauty9302 2.48; LettingOwnProp7020 2.26; ArtsFacilitiesOperation9232 2.20; OtherBusinessActivities7487 2.20; LibraryArchive9251 2.10; PhysicalWellBein9304 2.02; JournalsPublish2213 2.00;
Sutton	15,129	18,843	JournalsPublish2213 12.98; SocialServiceCompuls7530 7.90; RepairWatchesJewel5273 5.37; UndertakersFuneral9303 4.69; RetailHardware5246 4.45; GovernmentSupport7514 4.25; NonLifeInsurance6603 3.27; LibraryArchive9251 3.21; RetailTextiles5241 2.80;	RetailOtherNonspecial5212 2.80; RetailClothing5242 2.64; RetailFootwearLeather5243 2.60; LabourRecruitment7450 2.58; RetailBooksStation5247 2.57; MotionPictureProjection9213 2.55; PublicSecurityLawOrder7524 2.44; RetailCosmetics5233 2.39; InvestigationSecurity7460 2.22;

Table C.3: Wider Study Area Employment Centre Sectoral Specialisation
Data Source: Annual Business Index 1998-2002 (ONS, 2010c).

Centre Name	Employment (2001 Census)	Population (2001 Census)	Sectoral Specialisations (4 Digit SIC's with Location Quotient Greater than 2)	
Reading	94,456	111,520	LifeInsurance6601 7.38; NewsPrinting2221 5.67; BusinessRegulation7513 3.94; OtherCredit6522 3.70; Telecommunications6420 3.21;	ComputerManufacture3002 2.95; OtherSoftwareConsult7222 2.85; HigherEducation8030 2.50; Advertising7440 2.29; OtherPrinting2222 2.00;
Luton	73,295	146,070	NonScheduledAirTrans6220 15.15; ScheduledAirTransport6210 6.47; OtherAirTransport6323 5.64; RetailStallsMarkets5262 3.18; PublicServiceRegulation7512 3.18; DataProcessing7230 2.87;	RepairShoesLeather5271 2.63; RetailOtherNonStore5263 2.60; LabourRecruitment7450 2.32; RealEstateManage7032 2.30; ManagementHoldingComp7415 2.10; RetailOtherSpecial5248 2.03;
Crawley	72,282	37,573	NonScheduledAirTrans6220 36.55; OtherAirTransport6323 22.57; ScheduledAirTransport6210 12.86; RetailMedical5232 5.78; TravelAgenciestTours6330 5.19;	OtherTransportAgencies6340 4.84; DataProcessing7230 3.99; PharmaceuticalManfacture2442 3.86; InvestigationSecurity7460 3.62; SecondaryEduTechVoc8022 2.07;
Gillingham	51,286	139,577	OtherWaterTransport6322 5.19; CallCentreActivities7486 5.09; DefenceActivities7522 4.59; LifeInsurance6601 3.08; PhysicalWellBein9304 2.40; OtherHumanHealth8514 2.37;	SocialServiceCompuls7530 2.29; SecondaryEducaiton8021 2.26; GovernmentSupport7514 2.05; VetinaryActivities8520 2.02; LaundryDryClean9301 2.00;
Slough	50,156	80,601	CompMediaReproduction2233 31.29; RandDSocSci7320 19.78; PackagingActivities7482 7.06; Telecommunications6420 5.63; SoftwarePublish7221 4.91; CallCentreActivities7486 4.86; DataProcessing7230 3.92; RandDNaturalSciEng7310 3.27; RetailHardware5246 3.12;	HardwareConsult7210 2.71; OtherCredit6522 2.39; RepairElectrical5272 2.35; SportsArenasOperation9261 2.31; OtherSoftwareConsult7222 2.26; OtherComputer7260 2.23; ManagementHoldingComp7415 2.19; Advertising7440 2.13; LabourRecruitment7450 2.11;
Watford	42,784	50,174	NewsPrinting2221 35.47; OtherWaterTransport6322 13.87; Bookbinding2223 9.02; OtherCredit6522 8.88; FinancialLeasing6521 7.18; RepairWatchesJewel5273 4.88; ManagementHoldingComp7415 4.10; PrepressActivities2224 3.27; SocialServiceCompuls7530 2.88; RetailClothing5242 2.83; RetailOtherNonspecial5212 2.81;	OtherPrinting2222 2.61; RetailElectrical5245 2.56; OtherPublish2215 2.49; LaundryDryClean9301 2.47; LifeInsurance6601 2.46; RetailCosmetics5233 2.40; LabourRecruitment7450 2.37; RetailMailOrder5261 2.27; RetailFootwearLeather5243 2.05; Accountancy7412 2.04; RetailHardware5246 2.01;
Farnborough	42,538	43,460	PharmaceuticalManfacture2442 10.11; RetailBakers5224 5.77; BookPublish2211 5.19; MotionPictureProjection9213 4.04; OtherSoftwareConsult7222 3.44; FinancialInterAuxil6713 2.96; RetailHardware5246 2.70;	OtherService9305 2.68; SportsArenasOperation9261 2.58; InsuranceAuxil6720 2.49; ArchitectureEngineering7420 2.20; DataProcessing7230 2.20; RepairElectrical5272 2.17; TechnicalTesting7430 2.04;
Chelmsford	41,847	44,632	RepairElectrical5272 9.71; JusticeJudicialActivities7523 4.99; NonLifeInsurance6603 4.73; DatabaseActivities7240 4.13; PublicSecurityLawOrder7524 4.10; PublicServiceGeneral7511 3.44; LifeInsurance6601 3.25;	RetailTextiles5241 3.04; RetailHardware5246 2.85; OtherCredit6522 2.77; HigherEducation8030 2.75; LibraryArchive9251 2.53; RepairShoesLeather5271 2.30;
Hemel Hempstead	39,011	37,777	HardwareConsult7210 21.08; ComputerManufacture3002 10.28; StorageWarehousing6312 9.60; ManagementHoldingComp7415 9.39; RetailMailOrder5261 5.59; SecretarialTranslationServ7485 5.25;	TechnicalTesting7430 2.71; PhysicalWellBein9304 2.33; OtherComputer7260 2.15; OtherSports9262 2.15; RetailHardware5246 2.01;
Guildford	37,933	42,765	PharmaceuticalManfacture2442 7.85; HigherEducation8030 5.08; SecondaryEduTechVoc8022 4.79; NonLifeInsurance6603 3.94; BusinessRegulation7513 3.47;	RetailCosmetics5233 2.56; RetailFootwearLeather5243 2.44; RetailFurniture5244 2.07; RetailElectrical5245 2.02;
Southend	37,474	66,542	RepairWatchesJewel5273 15.07; CallCentreActivities7486 7.25; SecondaryEduTechVoc8022 5.21; BusinessRegulation7513 5.07; GamblingActivities9271 4.00; PublicServiceGeneral7511 3.50;	UndertakersFuneral9303 2.95; SocialWorkwAccom8531 2.79; SocialServiceCompuls7530 2.59; HospitalActivities8511 2.49; PhysicalWellBein9304 2.05;
High Wycombe	35,426	47,604	MarketResearch7413 13.85; CompMediaReproduction2233 10.44; DatabaseActivities7240 7.65; OtherRecreational9272 5.04; ComputerManufacture3002 4.58; ITMaintenance7250 4.29;	RetailOtherNonspecial5212 3.11; OtherCredit6522 2.59; PrepressActivities2224 2.33; HigherEducation8030 2.29; RetailBooksStation5247 2.20;

Stevenage	34,795	42,120	ITMaintenance7250 14.41; DataProcessing7230 9.47; RepairElectrical5272 9.12; RandDNaturalSciEng7310 8.26; PackagingActivities7482 3.59; RetailMailOrder5261 3.50; LifeInsurance6601 3.41; StorageWarehousing6312 3.08;	MotionPictureProjection9213 2.92; PrepressActivities2224 2.87; SocialServiceCompuls7530 2.61; LaundryDryClean9301 2.51; NonLifeInsurance6603 2.48; CallCentreActivities7486 2.43; FireService7525 2.18; HospitalActivities8511 2.08;
Basildon	34,763	44,822	FinancialInterAuxil6713 12.59; PackagingActivities7482 12.48; SocialServiceCompuls7530 8.80; OtherTransportAgencies6340 3.90; RetailOtherNonspecial5212 3.81; OtherPrinting2222 3.04; RetailHardware5246 2.89;	RetailClothing5242 2.41; MotionPictureProjection9213 2.32; RetailFurniture5244 2.26; JournalsPublish2213 2.21; TechnicalTesting7430 2.12; NewsPublish2212 2.09;
Maidstone	32,435	47,574	RetailMedical5232 17.03; GovernmentSupport7514 16.73; FireService7525 4.89; JusticeJudicialActivities7523 3.52; OtherHumanHealth8514 3.48; TechnicalTesting7430 3.42; RetailTextiles5241 3.23;	UndertakersFuneral9303 3.19; LibraryArchive9251 3.06; PublicServiceGeneral7511 2.79; SocialWorknoAccom8532 2.50; PrepressActivities2224 2.37; RetailCosmetics5233 2.32;
Bracknell	32,084	33,223	ITMaintenance7250 23.33; OtherCredit6522 12.44; ManagementHoldingComp7415 11.98; DataProcessing7230 11.23; DatabaseActivities7240 7.05; SecondaryEduTechVoc8022 5.92; RandDNaturalSciEng7310 5.90; PharmaceuticalManfacture2442 5.06; DefenceActivities7522 4.66;	OtherSoftwareConsult7222 4.23; CallCentreActivities7486 3.73; NewsAgencyActivities9240 3.33; MarketResearch7413 3.33; OtherBusinessActivities7487 2.80; ComputerManufacture3002 2.76; OtherRecreational9272 2.74; OtherComputer7260 2.55; MotionPictureProjection9213 2.38;
Harlow	30,986	42,977	RandDNaturalSciEng7310 12.60; CallCentreActivities7486 8.87; BookPublish2211 8.33; SoundPublish2214 5.81; FinancialLeasing6521 4.08; RetailOtherNonStore5263 3.95; MotionPictureProjection9213 3.69; PackagingActivities7482 3.38;	RetailHardware5246 3.07; RetailNewsagent5211 2.67; ITMaintenance7250 2.46; RepairWatchesJewel5273 2.43; RetailElectrical5245 2.18; VetinaryActivities8520 2.18; RetailOtherSpecial5248 2.01
Aldershot	29,840	50,512	DefenceActivities7522 15.30; ComputerManufacture3002 4.79; PrintingAncillary2225 3.92; RetailMedical5232 3.82; SoftwarePublish7221 3.03;	CompMediaReproduction2233 2.99; OtherSoftwareConsult7222 2.92; SportsArenasOperation9261 2.83; SocialServiceCompuls7530 2.05; HardwareConsult7210 2.04;
Grays	26,245	26,288	CargoHandling6311 17.27; RetailFurniture5244 11.38; StorageWarehousing6312 8.85; CallCentreActivities7486 8.05; OtherTransportAgencies6340 7.09; RetailFootwearLeather5243 6.91; RetailClothing5242 6.83; RetailOtherNonspecial5212 5.83; RetailCosmetics5233 4.53;	MotionPictureProjection9213 4.26; RetailOtherSpecial5248 3.84; RetailHardware5246 3.62; RetailElectrical5245 3.60; LaundryDryClean9301 2.82; RepairShoesLeather5271 2.60; TechnicalTesting7430 2.26; ComputerManufacture3002 2.22; RetailBooksStation5247 2.06;
Welwyn	25,909	31,079	PublicSecurityLawOrder7524 6.90; RetailAlcohol5225 5.88; RandDNaturalSciEng7310 5.59; StorageWarehousing6312 5.34; SportsArenasOperation9261 4.25;	RetailNewsagent5211 3.41; RetailOtherNonspecial5212 3.33; DatabaseActivities7240 2.84; SecretarialTranslationServ7485 2.32; InvestigationSecurity7460 2.00;
St Albans	25,225	51,828	MarketResearch7413 3.76; SecondaryEduTechVoc8022 2.49; Accountancy7412 2.21;	InsuranceAuxil6720 2.19; SocialWorkwAccom8531 2.16; SecondaryEducaiton8021 2.06;
Staines	21,394	19,371	OtherComputer7260 11.74; CargoHandling6311 7.20; ITMaintenance7250 7.19; NonLifeInsurance6603 6.42; RepairElectrical5272 5.40; RandDNaturalSciEng7310 5.22;	ManagementHoldingComp7415 4.01; OtherSoftwareConsult7222 3.62; MotionPictureProjection9213 2.99; OtherTransportAgencies6340 2.46; RetailMedical5232 2.24; OtherBusinessActivities7487 2.04;
Maidenhead	21,187	29,002	PhysicalWellBein9304 15.50; Telecommunications6420 5.65; SecretarialTranslationServ7485 5.02; MarketResearch7413 4.81; SoftwarePublish7221 4.33; RepairElectrical5272 4.15; OtherSoftwareConsult7222 3.55; TechnicalTesting7430 3.37; RetailOtherSpecial5248 3.01;	OtherBusinessActivities7487 2.99; LaundryDryClean9301 2.75; MotionPictureProjection9213 2.71; Advertising7440 2.23; RetailOtherNonStore5263 2.21; ManagementHoldingComp7415 2.07; RepairOther5274 2.04; OtherPrinting2222 2.01;
Dunstable	21,076	53,207	FinanceMarketAdmin6711 12.20; ComputerManufacture3002 12.20; SecondaryEduTechVoc8022 6.52; StorageWarehousing6312 5.54; ITMaintenance7250 4.25; BookPublish2211 4.19; OtherPrinting2222 3.96; RepairElectrical5272 3.86; RetailOtherSpecial5248 3.59; RetailFurniture5244 3.48;	RetailHardware5246 2.52; RetailNewsagent5211 2.42; RetailMailOrder5261 2.33; OtherHumanHealth8514 2.32; RepairOther5274 2.17; TechnicalTesting7430 2.12; VetinaryActivities8520 2.11; PackagingActivities7482 2.05; RetailTextiles5241 2.00;

Reigate	20,589	28,448	FinancialLeasing6521 83.01; LifeInsurance6601 9.13; InsuranceAuxil6720 6.78; ArtsFacilitiesOperation9232 3.73; NonLifeInsurance6603 3.66; ITMaintenance7250 3.59; BookPublish2211 3.38;	JournalsPublish2213 3.23; RetailTextiles5241 2.75; ArchitectureEngineering7420 2.34; OtherCredit6522 2.17; SocialServiceCompuls7530 2.16; RetailSeaFood5223 2.13;
Woking	18,908	20,786	OtherLandTransport6321 9.82; OtherSoftwareConsult7222 4.71; PrintingAncillary2225 4.54; SoftwarePublish7221 4.15; OtherComputer7260 3.99; ArtsFacilitiesOperation9232 3.64; SocialServiceCompuls7530 2.87;	HardwareConsult7210 2.83; TravelAgenciestTours6330 2.60; PublicServiceRegulation7512 2.39; DatabaseActivities7240 2.29; RetailBooksStation5247 2.16; LabourRecruitment7450 2.06; SecretarialTranslationServ7485 2.02;
Wokingham	18,571	29,726	RandDSocSci7320 13.31; ComputerManufacture3002 7.01; OtherComputer7260 6.69; MotionPictureProjection9213 6.23; DatabaseActivities7240 4.86; RandDNaturalSciEng7310 4.48; ITMaintenance7250 4.40; OtherSoftwareConsult7222 4.12;	Telecommunications6420 3.57; HardwareConsult7210 3.50; DataProcessing7230 3.07; OtherHumanHealth8514 2.78; PhysicalWellBein9304 2.58; SoftwarePublish7221 2.37; NewsPrinting2221 2.17; RetailOtherNonStore5263 2.06;
Hertford	18,090	19,436	GovernmentSupport7514 15.44; PublicServiceRegulation7512 10.27; PublicServiceGeneral7511 5.35; OtherPrinting2222 4.44; FireService7525 4.13; NonLifeInsurance6603 4.05; RetailSeaFood5223 3.96; RepairShoesLeather5271 3.41;	Bookbinding2223 3.40; SocialServiceCompuls7530 3.32; JournalsPublish2213 3.22; LabourRecruitment7450 3.01; PhotographicActivities7481 2.87; RandDSocSci7320 2.48; PackagingActivities7482 2.18; VetinaryActivities8520 2.06;
Gravesend	15,111	25,577	OtherWaterTransport6322 74.10; GovernmentSupport7514 7.56; CargoHandling6311 5.16; UndertakersFuneral9303 4.97; SocialServiceCompuls7530 4.74; StorageWarehousing6312 4.56; RepairWatchesJewel5273 4.30; PublicSecurityLawOrder7524 4.12;	RetailHardware5246 3.49; RetailMedical5232 2.87; PublicServiceGeneral7511 2.47; RetailFurniture5244 2.37; RetailOtherNonspecial5212 2.37; RetailOtherNonStore5263 2.17; RetailTextiles5241 2.06; RetailSeaFood5223 2.01;
Borehamwood	15,045	28,546	PhotographicActivities7481 14.25; RetailMailOrder5261 9.65; NonLifeInsurance6603 7.39; Telecommunications6420 5.11; ITMaintenance7250 4.61; StorageWarehousing6312 3.43; PrintingAncillary2225 3.15;	MotionPicutreVidProduc9211 2.83; OtherSports9262 2.49; RepairShoesLeather5271 2.47; LettingOwnProp7020 2.46; MarketResearch7413 2.22; RadioTelevisionActiv9220 2.17; LabourRecruitment7450 2.10;

Appendix D: Greater London Real-Estate Analysis

This appendix describes how the Valuation Office data can be processed to create a real-estate database of non-domestic property in Greater London. This involves processing the data, classifying properties into functional groups and georeferencing the data for spatial analysis. The Valuation Office Agency (VOA) conducts valuation surveys of properties in England and Wales for purposes of local taxation (Bruhns, 2000). Their surveys are split into domestic rates and business rates, with the 2005 business rates analysed here (the survey is updated every five years). The basic unit of analysis are premises, which are defined as contiguous properties with a single business occupier. The comprehensiveness of the data for non-residential property is unparalleled in any UK dataset (Bruhns, 2000), and the accuracy of data should be high given the legal taxation status of VOA listings.

Data processing is required to produce a manageable spatial database from the VOA listings, involving data cleaning, restructuring, and generalising several hundred use descriptions into aggregate classes. The classification structure used here is presented in Table D.1, grouping premises into office, retail, industrial, local service and public service super-groups, with further division of sub-group categories. This classification is intended to provide a general overview of urban functional structure. The VOA data only records floorspace data for a subset of commercial properties, while rateable value information is recorded for all properties. This subset are termed the 'bulk' classes (Bruhns, 2000), and are grouped here as office, retail and industrial activities. Floorspace analysis is therefore restricted to these groups. These groups are the most frequent in terms of premises, representing 85% of the total.

The data was spatially referenced to postcode units using the 2005 National Postcode Directory File centroids. Two zonal data aggregations of the postcode unit data are used here. The first links the VOA data to 2001 census wards, allowing comparison with census based socio-economic geography. The second aggregation is used for the main tasks of visualisation and spatial analysis of the real-estate database. A grid-based approach has been chosen here to avoid problems of irregular socio-economic zones (see Section 4.3) and facilitate statistical analysis and visualisation. The regularity of grid square areas means that zone totals become standardised density statistics across the study area. Using postcode unit centroids as the means of aggregation will introduce some modifiable areal unit errors. These increase as the grid resolution increases (as more postcode units traverse grid square boundaries). A grid resolution of 500 metres was

chosen to provide sufficient intra-urban detail whilst remaining significantly coarser than postcode unit geography to minimise MAUP errors.

Table D.1: Functional Groups and Property Types

Super-Group	Group	General Property Types	Premises Total (%)	Premises Total	Floorspace Data
Office	Office	Offices, business premises, office banks, law courts, town hall, TV studios.	32.3%	74,765	Y
Retail	Retail	Shop, department store, supermarket, kiosk.	34.0%	78,808	Y
	Supermarket	Supermarket, superstore.	0.1%	244	Y
Industrial	Industrial	Warehouse, store, workshop.	18.4%	42,765	Y
	Factory	Factory, works.	1.0%	2,333	Y
Local Services	Local Services	High street bank, building society, community centre, laundrette, hairdresser, betting shop, library, post office, youth centre.	3.1%	7,204	N
	Leisure	Gallery, bingo hall, cinema, gym, leisure centre, museum, night club, theatre.	1.0%	2,234	N
	Restaurant	Bar, café, public house, restaurant.	5.8%	13,365	N
Public Services	Education	School, nursery, college, university, education centre.	1.9%	4,326	N
	Health	Hospital, clinic, surgery, health centre.	1.9%	4,403	N
	Emergency Services	Fire station, police station.	0.1%	289	N
	Hotel	Hotel, guest house, hostel.	0.5%	1,261	N

The real-estate database can be joined to socio-economic zones to test relationships between physical structure and employment data. The comparison of real-estate totals against employment totals provides a basic means of validating the data. There is no ideal source of employment data at a matching spatial and temporal resolution to the real-estate data. Data from the 2001 census travel to work data has been used as the employment data source. While the four year temporal discrepancy between the datasets is problematic, the census data has the advantage of being a comprehensive sample at relatively high spatial resolution.

There are close relationships between both rateable value and employment, and floorspace and employment at ward level, as shown in Figure D.1, illustrating a close correspondence between the built-environment and employment geography. Outliers in the graphs include areas of rapid employment growth (particularly the Canary Wharf business centre) where the four year temporal discrepancy leads to the 2001 employment measure under-predicting built-environment intensity.

Heathrow airport is also problematic, as floorspace data is not provided for airports in the survey, causing the airport zone to be a major outlier in Figure D.2. Relationships between floorspace and employment were found to be weaker for the industrial groups compared to office and retail activities. This can be explained by relatively low levels of employment occupation in industrial premises compared to offices and shops.
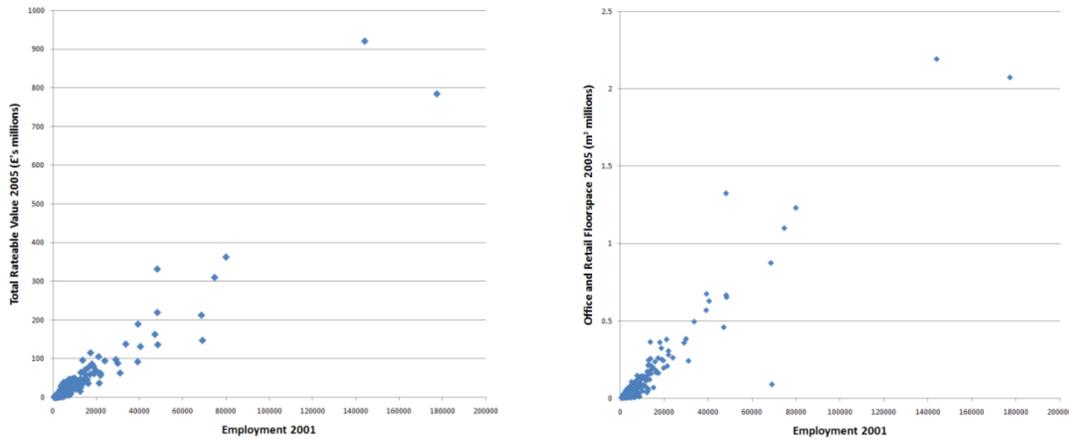
Figures D.1 & D.2: Graphs of relationships between total rateable value and employment (left), and office-retail floorspace and employment (right) at census ward level.

The varying demands of firms and public agencies for types of premises, in terms of accessibility, property size (connected to economies of scale) and ability to meet rental costs will be reflected in the property statistics for the functional groups in the real-estate database. The results for the bulk groups (with floorspace information) in terms of mean size and value are shown in the top half of Table D.2. The two most prevalent groups are retail and office, which together account for over two thirds of all premises. Offices are on average twice as large as retail premises, and therefore account for a significantly larger total rateable value (over £5 billion in total estimated annual rent). The ratio of rateable value to floorspace allows a like-for-like comparison of property value. Office is the highest category at over £205 £/m², with retail marginally lower at £189 £/m². The industrial and factory groups in contrast are unsurprisingly of much lower value, whilst having larger mean floorspaces. This reflects bid-rent type processes trading-off accessibility and property size depending on economic function. Large economies of scale can be seen in the factory and supermarket groups. Interestingly the supermarket group has a high value-to-floorspace ratio despite having a very large average floorspace size, indicating that for the London example these premises are likely in accessible locations and are of high specification.

For the remaining functional groups floorspace data is absent, and so the analysis is restricted to rateable value. The number of premises for these groups is a small fraction of the office, retail and industrial groups, and the total rateable value is consequently minimal. There are several groups with large mean rateable value results, namely the Leisure group (which includes theatres and cinemas), the Emergency Services group (which includes hospitals) and the Hotel group.

Note that the statistical distribution of premises size do not follow a normal distribution curve around the mean, but instead display a long-tail distribution, with the number of premises declining as floorspace or rateable value increases (Figure D.3). This is typical of scaling distributions found in many urban phenomena, from city size distributions to the geometry of buildings (Batty *et al.*, 2008). The histogram curves are distinct for each functional group. Interestingly the retail group has a higher modal value than the office and industrial groups, but a lower mean floorspace as the retail curve declines more steeply.

Table D.2: Functional Groups Summary Statistics for Greater London

Functional Group	Premises Total	Floorspace Total (millions m²)	Rateable Value Total (millions £'s)	Mean Floorspace (m²)	Mean Rateable Value (£)	Value to Floorspace Ratio (£ / m²)
Office	74,765	24.7	5,050	330	67,500	204.5
Retail	78,808	10.6	2,000	135	25,400	188.7
Supermarket	244	1.3	219	5,153	895,377	173.7
Industrial	42,765	17.7	1,270	414	29,700	71.8
Factory	2,333	3.3	152	1,415	44,404	46.1

Functional Group	Premises Total	Floorspace Total (millions m²)	Rateable Value Total (millions £'s)	Mean Floorspace (m²)	Mean Rateable Value (£)	Value to Floorspace Ratio (£ / m²)
Local Services	7,204	-	172	-	23,849	-
Leisure	2,234	-	229	-	102,294	-
Restaurant	13,365	-	540	-	40,460	-
Education	4,326	-	388	-	89,639	-
Health	4,403	-	209	-	47,459	-
Emergency Services	289	-	42	-	146,966	-
Hotel	1,261	-	347	-	274,880	-
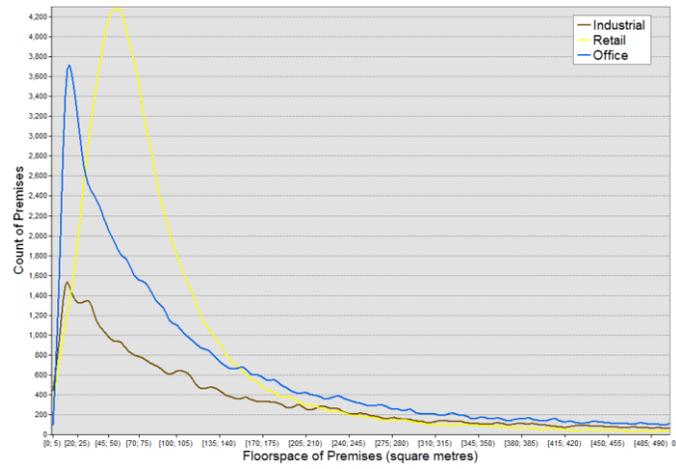
Figure D.3: Histogram of Commercial Functional Groups and Floorspace

Appendix E: Modelling Transport Network Accessibility in the London Region

E.1 Public Transport Network Representation

The initial network for public transport trips is the pedestrian street network, with walking invariably comprising the first and last stages of a journey. The Ordnance Survey ITN road layer has been used for the geometric representation of streets, as shown in Figure E.1. This is a detailed representation, though does not currently include pedestrian-only paths, such as routes through public parks[1]. An essential step for enabling multi-modal trips is to link the pedestrian network to public transport stations. A geoprocessing operation was performed to automatically link all public transport nodes to the nearest street junction, allowing pedestrian-underground interchange as illustrated in Figure 6.3.
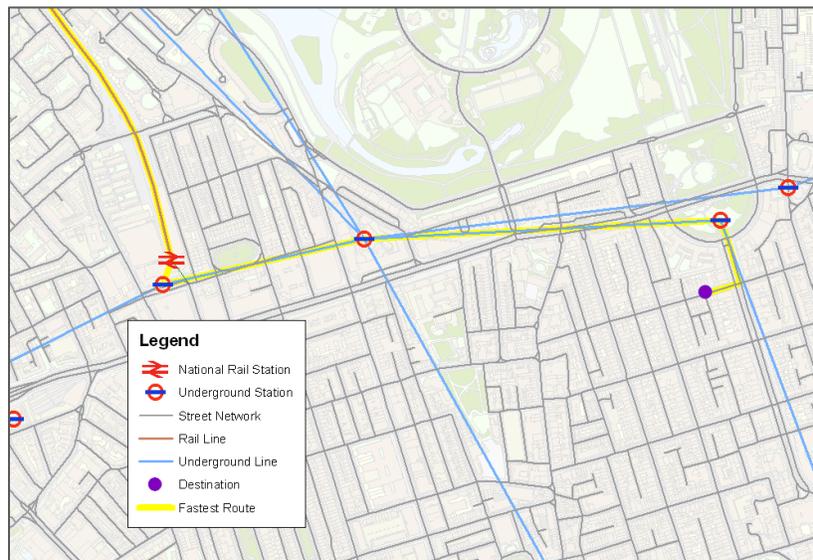
Figure E.1: Example Multimodal Rail-Underground-Pedestrian Network Route. Data Sources: Ordnance Survey 2007b, NAPTAN.

---

[1] This is less of an issue for the metropolitan scale analysis pursued here, though could become problematic for finer scale studies. Note Ordnance Survey are overcoming this data gap with an urban paths network layer.

Each of the major public transport networks- mainline rail, light rail and bus- have unique characteristics in their operation and coverage, and so were modelled individually before being brought together to form an integrated network. The representation of the mainline rail infrastructure is based on an edited version of the Ordnance Survey Meridian 2 data. This is topographic vector data, and allows accurate calculation of rail distances between stations. The rail network has several unique characteristics compared to other public transport modes, namely the wide variation in operational speeds between services, and the characteristic of trains being able to 'skip' local stations, in contrast to metro lines where trains stop at every station. This makes a service based representation (with a separate network representation for each rail service) the most suitable solution for accurately calculating rail journey times. While the link times can be based directly on rail timetables, the large number of rail services into London (over 150) would make this a laborious task. An alternative geometry based solution has been used here where rail services have been classified into general speed groups derived from a sample of timetabled services. The groups are shown in Table E.1 and mapped in Figure E.2.

Table E.1: Rail Service Speed Classes

Rail Speed Group	Speed (km/h)	Example Rail Lines
High Speed	170	HS1 (St Pancras – Ashford)
Moderate High	150	Great North Eastern
Moderate	115-150	Great Western, Western Main Line
Local	90	Guildford, Maidstone, Croydon
Low-congested	30-65	Thameslink

As can be seen in Figure E.2 the vast majority of services are grouped in the 90 km/h class. Faster lines relate to upgraded long distance lines such as the Great North Eastern and Great Western lines. This results in a northern and western bias to the higher speed infrastructure. Additionally the fastest line in the UK is High Speed 1 (HS1), which provides domestic services to Ashford and beyond and uses the same infrastructure as the Channel Tunnel Rail Link.
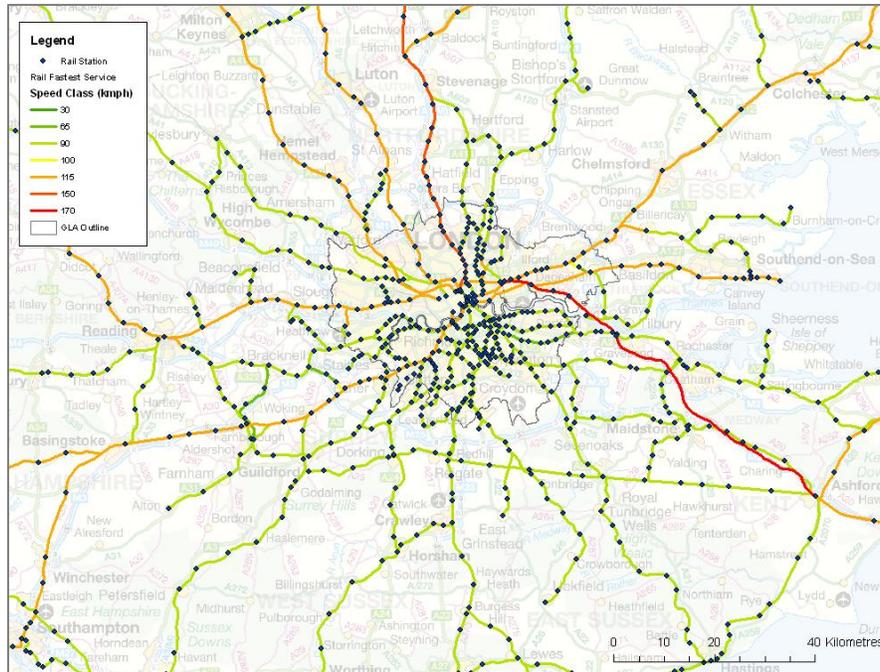
Figure E.2: Mainline Rail Network, with Speeds of Fastest Services. Data Sources: Ordnance Survey 2007c, NPTDR 2010.

Using the service-based network described above, the travel times between rail links are calculated based on the distance, service speed and a station delay (representing the time delay of the train decelerating and stopping) as illustrated in Figure E.3. While this approach is less accurate than including the full timetable, comparison with timetable data found errors to be on average 3% and not exceeding 10% of travel time. The approach also has advantages in being faster to implement, and could be used to estimate travel times for future rail infrastructure where timetables do not yet exist.
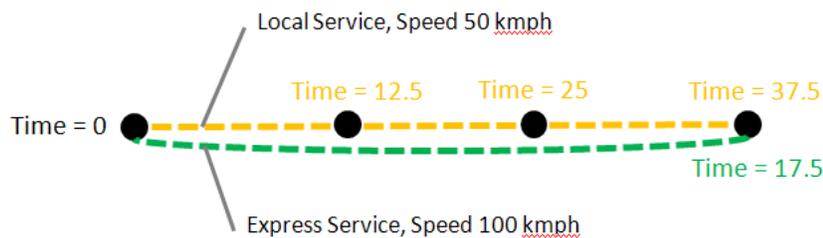
Figure E.3: Service Based Representation of the Rail Network, Allowing Variable Speeds and Passing Stations

359

For the London Underground network, topographic mapping data sources do not provide the network geometry. There are security concerns regarding the availability of detailed mapping of the tube network. Station locations are provided through the publically available NAPTAN data. Consequently a topological network has been employed here, with straight lines linking underground stations. This makes geometric distances less reliable, and timetabled frequencies and journey times between stations have been used. As the Docklands Light Railway and London Overground networks are closely integrated with the underground, these have also been represented using the same methodology. The resulting network is presented in Figure E.4.
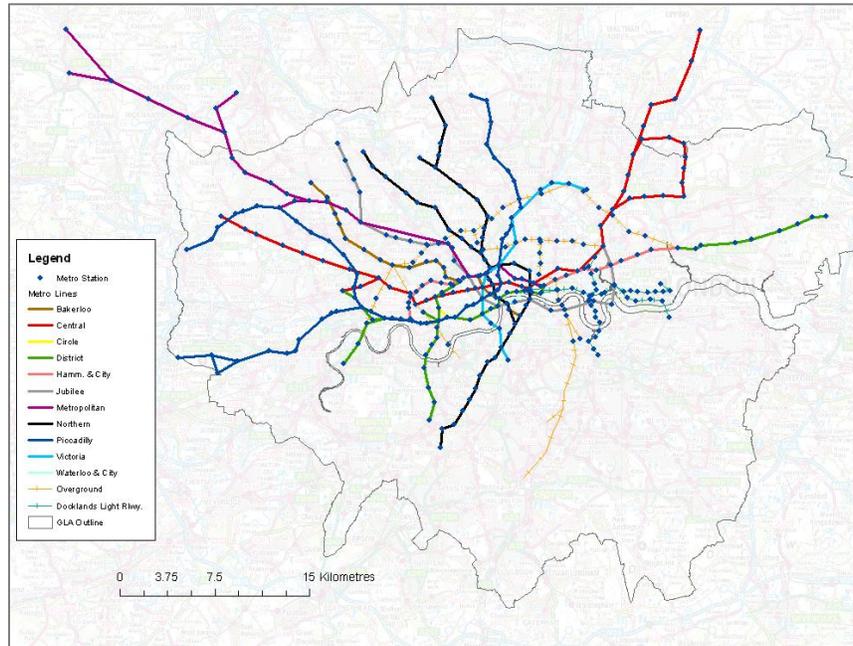
Figure E.4: Underground, DLR and Overground Topological Network Representation.
Data Source: NAPTAN.

The bus network is also appropriate for a service based representation, due to the wide variation in bus service routes and frequencies. There are two problems that have prevented a full representation of the bus network being employed in this model. The first is the sheer volume of bus services in London and the South East. A fully automated method of generating the network from timetable databases is required, as opposed to the semi-manual approach used for the rail and underground networks described above. Time limits on this research have prevented this development. The second problem is that during peak times bus services are affected by congestion in London, to the point of making timetabled journey times potentially inaccurate. For the purposes of this research a simple proxy network has been built. Road links with bus stops have been joined to the core road network, and the density of bus stops in a 2 km radius has been

360

used to estimate wait times, as shown in Figure E.5. The speeds of buses on links are estimated based on a reduced factor of private vehicle speeds.
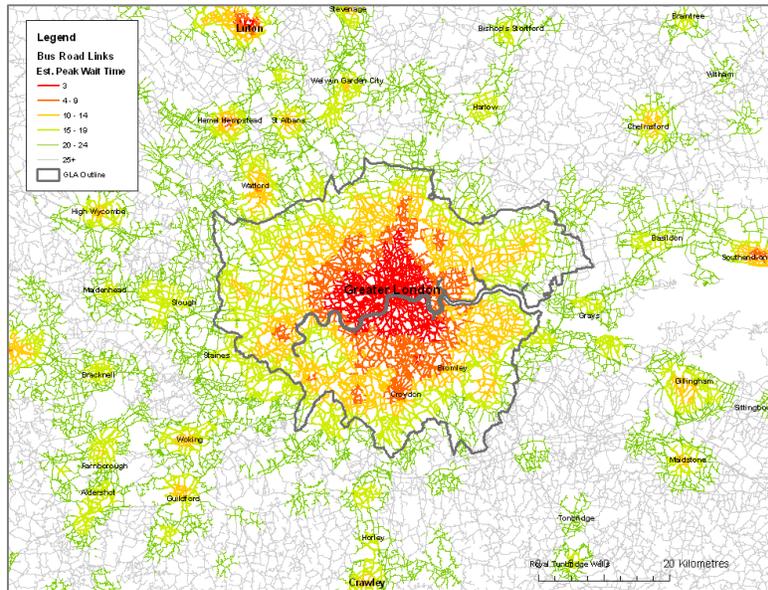
Figure E.5: Bus Network Representation Links and Estimated Wait Times.
Data Sources: Ordnance Survey 2007b, NAPTAN.

E.2   Public Transport Costs and Interchanges

The two key challenges in the analysis are the accurate calculation of travel costs on a link by link basis, and secondly identifying where interchanges take place (and adding appropriate travel costs when they do). This research uses travel time as the measure of travel cost. This could be modified to generalised costs using the same structure with additional coefficients for each journey stage.

To allow the integration of the pedestrian, rail, underground and bus networks, each link is given the same database attribute structure as presented in Table E.2. In the model each service must have a unique ID to determine when interchanges occur. Essentially when moving between links with the same Service ID no wait time delays are applied, as shown in Figure E.6. The procedures for forming the Service ID's are particular to each mode, as shown in Table E.3. Note that pedestrian links all have the same Service ID as there are no interchanges on this mode. Additionally the pedestrian Wait Time is 0, as alighting from a public transport service to the street network incurs no wait delay. The wait times for public transport services are calculated as the standard half of the service headway, or in minutes 30/Service Frequency.

Table E.2: Field Definitions

Link Attribute	Definition
Mode	Mode ID
Service ID	Unique ID for public transport service for identifying interchanges
Link Time	Time for service to traverse the link
Wait Time	Average wait time at the platform/stop to board this service
Link Length	Distance of link

Table E.3: Field Calculations for Modes

Mode	Service ID	Link Traversal Time	Interchange Wait Time
Pedestrian	1	Street Length / 5 kmph	0
Underground	2 [LineID] [BranchID]	Timetable	30 / Service Frequency
DLR/Overground	3 [LineID] [BranchID]	Timetable	30 / Service Frequency
Rail Mainline	4 [TerminusID] [ServID]	Link Length / Speed Class + stop delay	30 / Service Frequency
Bus	5 [ServiceID]	Link Length / Speed Class + stop delay	Stop density classification

Figure E.6: Core Algorithm for Identifying Service Interchange Delays.

Overall the methodology presented here allows the calculation of accurate network travel costs for multi-modal public transport journeys in the London region. This is a significant step for understanding accessibility and travel patterns, as discussed throughout this chapter. Transport models are generally geared towards car travel and typically do not consider public transport interchanges in detail, nor model 'softer modes' such as pedestrian at the street network level pursued here. Note this is not however a full transport model in the sense that capacity is modelled. Journey costs do not depend on the travel decisions of other users, as defined through

the iterative four stage transportation modelling process. The approach used here captures accessibility at a moment in time, but lacks the predictive capacity of a more sophisticated transport model.

E.3 Private Transport Network Accessibility

Private transportation accessibility is from one perspective more straightforward to model than public transport, as the issue of interchange is largely avoided. Calculating accurate travel costs for car journeys does however introduce different modelling challenges in terms of including the key factor of congestion on journey times, and additionally the significant issue of car parking costs (which are not directly modelled in this research). Similarly other private transport modes such as cycling have their own unique journey cost characteristics. As with the public transport model, the intention here is to capture the accessibility properties of the London region transportation system at the present time, rather than provide a dynamic predictive transportation model. The most novel technique applied here is the inclusion of GPS-derived data to calculate detailed properties of the road network based on real world journeys.

The geometric representation of the road network for this analysis is again based on the Ordnance Survey ITN data. This includes all public vehicle roads as well as associated road attributes such as the transportation authority classification. The road classification for the region is presented in Figure 6.8. Note that the overriding aim of the road classification framework is to provide an arterial or hierarchical network; that is to cater for car journeys by allowing drivers to move up and down the classification hierarchy, and to carry the largest volume of traffic on the major higher speed/capacity roads, namely motorways and a-roads. Consequently, better connectivity is provided the higher the road class, with the motorway network highly connected, whilst local and minor routes are more isolated and rely on the other road classes for connectivity.

In the methodology used here the journey times are comprised of the times on individual road links based on average speeds. It is useful to consider whether road classifications could be used as a reliable indicator of link based speeds. Unfortunately the same road classes can refer to roads that are variable in context and speed. Thus for example a-roads classifications can refer to single and dual carriageway links, in both congested urban and relatively free-flowing rural settings. Therefore road classification data on its own is not an accurate means of estimating speeds, particularly for highly congested regions such as London.
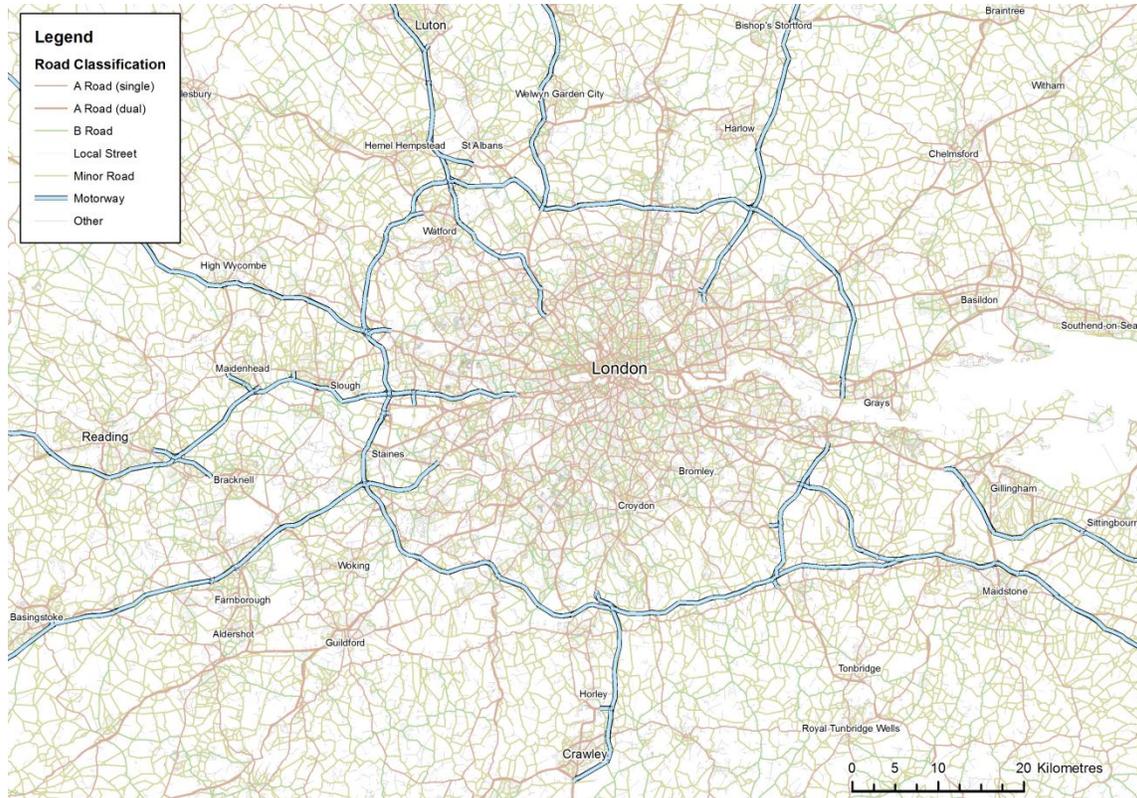
Figure E.7: South East Road Classification. Data Source: Ordnance Survey 2007b.

A solution to the problem of estimating speeds comes from recent GPS-based data sources that measure actual road performance from the trip patterns of vehicles. Transport for London (TfL) have provided GPS-derived data for this research sourced from the commercial firm ITIS. This data integrates a high number of GPS journey trails from various company and government vehicle fleets. The task of processing the GPS data and validating it against other speed surveys has been performed by TfL (Transport for London, 2005). The data records average travel properties or links during a period of one month, May 2007, with a total of 1.38 million link observations over the AM peak period. This is a large enough survey to provide speeds for a comprehensive network of major routes in Greater London, as shown in Figure E.8. Note that the original ITIS data is bi-directional with two speeds recorded for two way roads. This allows trends such as tidal congestion to be included. Bi-directional variation is not shown in Figure E.8, though this data is included in the subsequent network analysis.
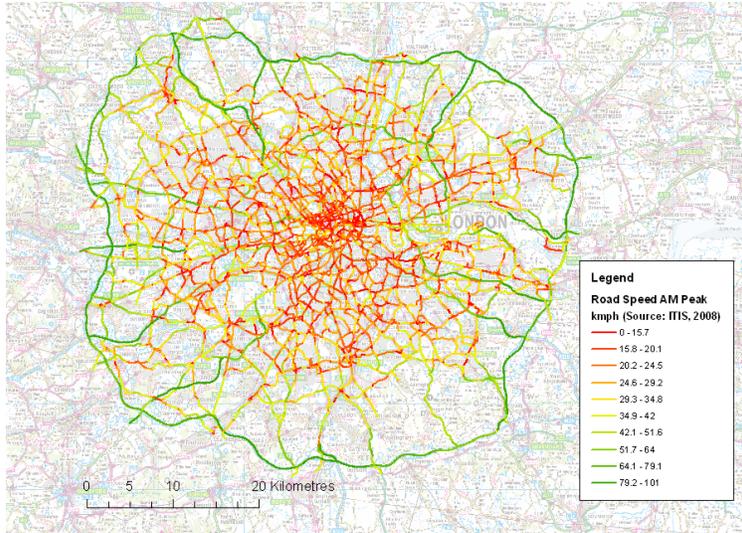
Figure E.8: Greater London Road Speeds. Data Source: ITIS Holdings, 2007; Ordnance Survey 2007b.

The ITIS data is a rich base from which to calculate road journey times in the study area. There are however two issues for this application relating to missing data, namely the lack of speeds for local roads within Greater London and secondly the speeds of roads beyond the M25. Data on local roads is sparser in the ITIS data as these roads are used infrequently and so are less likely to have a sufficient sample of GPS traces recorded. These local roads were assigned speeds based on the average local road speed in the particular sub-region where the road is located; the three sub-regions used being Inner London, Outer London and the Outer Metropolitan Area. The TfL data does not include journeys outside of the M25, and so another GPS datasource, Ecourier data, has been used for the major roads in the Outer Metropolitan Area. This data is for October 2007, also for AM peak. To ensure a close correspondence between these data sources, the Ecourier data (which unlike the ITIS data has not been thoroughly validated) was calibrated against the ITIS data using the Greater London links that have recorded speeds for both datasets.
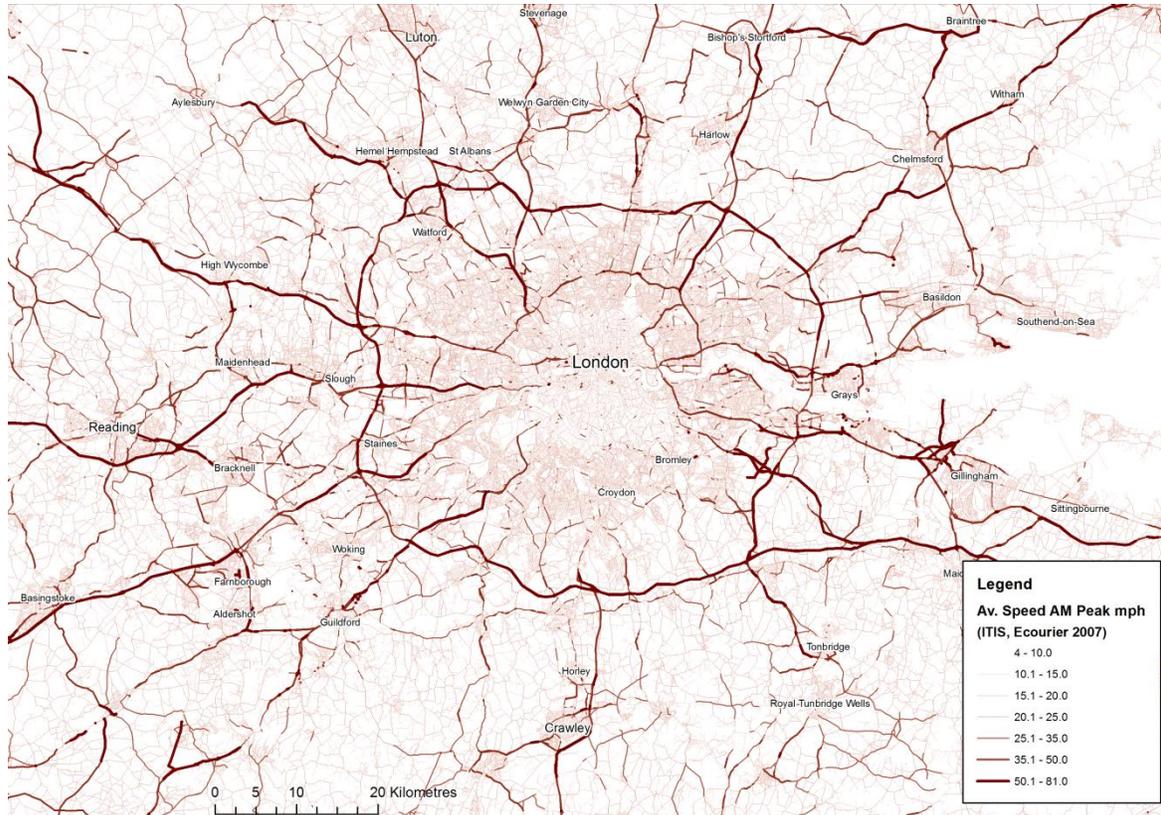
Figure E.9: Greater London Road Speeds. Data Sources: ITIS Holdings 2007, produced by the TfL Road Network Performance Team; Ecourier 2007; Ordnance Survey 207b.

There is great potential for future research to expand this technique of combining road network and GPS-derived data. This could include analysing the dynamics of congestion by comparing daily, weekly and annual cycles; considering the reliability of journeys choices rather than basic averages; and additionally applying GPS techniques to other modes such as buses and cycling where similar accessibility insights are possible. This research is confined to focussing on the first step of studying typical car journeys in the AM peak period.

Appendix F: Sub-Regional Journey-to-Work Flows by Mode

Table F.1: Total Journey to Work Flows, London Sub-regions.

Data Source: Census 2001 (ONS, 2010b).

| | | Destination Sub-Region | | | | |
		Central	Inner	Outer	OMA	GSER
Origin Sub-Region	Central	54,030	20,161	5,130	1,827	661
	Inner	344,602	404,343	103,251	23,622	4,842
	Outer	404,073	311,147	1,147,782	160,599	11,224
	OMA	203,316	92,163	259,695	2,104,186	104,253
	GSER	48,375	20,703	29,923	197,425	2,643,732

Table F.2: Walking and Cycling Journey to Work Flows, London Sub-regions
Data Source: Census 2001 (ONS, 2010b).

| | | Destination Sub-Region | | | | |
		Central	Inner	Outer	OMA	GSER
Origin Sub-Region	Central	24,195	4,302	277	81	90
	Inner	31,568	97,387	5,850	462	368
	Outer	5,512	11,258	170,935	2,942	518
	OMA	819	730	3,973	322,295	3,449
	GSER	759	538	803	4,315	494,420

Table F.3: Public Transport Journey to Work Flows, London Sub-regions.
Data Source: Census 2001 (ONS, 2010b).

| | | Destination Sub-Region | | | | |
		Central	Inner	Outer	OMA	GSER
Origin Sub-Region	Central	23,641	11,685	3,115	885	301
	Inner	271,312	187,851	49,445	8,624	2,117
	Outer	346,332	171,938	286,633	26,068	2,536
	OMA	174,608	49,478	26,017	148,769	6,700
	GSER	40,966	13,066	4,974	14,136	187,137

Table F.4: Car, Motorcycle & Taxi Journey to Work Flows, London Sub-regions
Data Source: Census 2001 (ONS, 2010b).

		Destination Sub-Region				
		Central	Inner	Outer	OMA	GSER
Origin Sub-Region	Central	6,194	4,174	1,738	861	270
	Inner	41,722	119,105	47,956	14,536	2,357
	Outer	52,229	127,951	690,214	131,589	8,170
	OMA	27,889	41,955	229,705	1,633,122	94,104
	GSER	6,650	7,099	24,146	178,974	1,962,175

Appendix G: Journey-to-Work Regression Analyses Tables

Table G.1: Independent Variables Analysed

Variable Category	Variable Group	Variable	Parameter Values Tested	Log Variable Tested	Aggregate Ward Spatial Referencing	Flow Data Availability	Data Source
Built Environment / Accessibility	Accessibility	Accessibility to Population by Public Transport	x = 1.1, 1.2, 1.3 ... 3	Yes	Residence, Workplace.	-	Accessibility model (see Section 6.1)
		Accessibility to Population by Road	x = 1.1, 1.2, 1.3 ... 3	Yes	Residence, Workplace.	-	
		Accessibility to Employment by Public Transport	x = 1.1, 1.2, 1.3 ... 3	Yes	Residence, Workplace.	-	
		Accessibility to Employment by Road	x = 1.1, 1.2, 1.3 ... 3	Yes	Residence, Workplace.	-	
	Jobs / Housing Balance	Access to Emply. by Road / Access to Pop. By Road	x = 1.1, 1.2, 1.3 ... 3	Yes	Residence, Workplace.	-	
		Access to Emply. by PT / Access to Pop. by PT	x = 1.1, 1.2, 1.3 ... 3	Yes	Residence, Workplace.	-	
	Density	Population Density	-	Yes	Residence, Workplace.	-	Census 2001
		Employment Density	-	Yes	Residence, Workplace.	-	
		Activity Density	-	Yes	Residence, Workplace.	-	
	Commercial Rental Value	Commercial Rental Value	-	No	Workplace.	-	VOA 2005
Socio-Economic / Demographic	Household Structure	Single Households %	-	No	Residence.	Yes	Census 2001
		Couple Households %	-	No	Residence.	Yes	
		Households with dependent children %	-	No	Residence.	No	
	Car Ownership	Cars to Households Ratio	-	No	Residence.	No	
		Households with 1 or more cars %	-	No	Residence.	No	
	Employment Specialisation	Management %	-	Yes	Residence, Workplace.	Yes	
		Professional %	-	Yes	Residence, Workplace.	Yes	
		Airport Function %	-	Yes	Workplace	No	ABI 1998-2002
	Household Income	Household Income	-	No	Residence.	No	Office for National Statistics
Trip Cost	Absolute Trip Cost	Journey Distance by Car	-	No	-	Yes	Accessibility model (see Section 6.1)
	Relative Trip Cost	Relative Time Car vs. Public Transport (mins faster by car)	-	Yes	-	Yes	
		Relative Time Car vs. Public Transport (% faster by car)	-	Yes	-	Yes	

G.1   Mode-Choice Regression Analyses

Table G.2: Interaction Ward Mode-Choice Models Goodness-of-Fit

Model Number	Dependent Variable	Independent Variables Excluded	Weighting Variable	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	Car Journey-to-Work % by Ward Interaction	Trip Cost	Flow magnitude	.924	.854	.854	95.13
2	Car Journey-to-Work % by Ward Interaction	Trip Cost, Car Ownership.	Flow magnitude	.917	.842	.842	99.13
3	Car Journey-to-Work % by Ward Interaction	Trip Cost, Car Ownership.	Flow magnitude	.892	.796	.796	112.73

Table G.3: Model 1 Coefficients

Variables	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics	
	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
(Constant)	153.008	1.470		104.058	.000		
Workplace Accessibility to Employment (PT, x=1.7, log)	-18.298	.163	-.455	-112.021	.000	.190	5.268
Flow Relative Car to PT Time (mins faster by car)	.556	.005	.301	116.886	.000	.474	2.109
Car Ownership (households with 1+ car %)	.773	.010	.367	74.267	.000	.128	7.789
Workplace Commercial Rental Value (VOA estimate)	-.055	.001	-.138	-51.536	.000	.435	2.300
Residence Accessibility to Population (PT, x=1.7)	.002	.000	.236	47.503	.000	.128	7.842
Residence Household Income (ONS estimate)	-.017	.001	-.090	-30.238	.000	.357	2.799
Workplace Employment Special. 2 (Professional %)	-.173	.007	-.071	-24.780	.000	.387	2.584
Workplace Employment Special. 1 (Management %)	.107	.015	.016	7.121	.000	.638	1.567

Table G.4: Model 2 Coefficients

Variables	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics	
	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
(Constant)	218.879	1.222		179.167	.000		
Workplace Accessibility to Employment (PT, x=1.7, log)	-18.947	.156	-.472	-121.416	.000	.226	4.428
Flow Relative Car to PT Time (mins faster by car)	.573	.005	.310	117.854	.000	.492	2.032
Residence Single Households (%)	-.408	.009	-.103	-45.724	.000	.668	1.496
Workplace Commercial Rental Value (VOA estimate)	-.052	.001	-.131	-47.322	.000	.443	2.255
Residence Household Income (ONS estimate)	.010	.000	.052	26.981	.000	.922	1.085
Workplace Employment Special. 2 (Professional %)	-.145	.007	-.059	-19.998	.000	.392	2.552

Table G.5: Model 3 Coefficients

Variables	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics	
	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
(Constant)	302.845	1.116		271.323	.000		
Workplace Accessibility to Employment (PT, x=1.7, log)	-27.187	.158	-.676	-172.369	.000	.286	3.498
Residence Single Households (%)	-.670	.010	-.169	-67.619	.000	.701	1.427
Workplace Commercial Rental Value (VOA estimate)	-.043	.001	-.107	-34.178	.000	.446	2.240
Residence Household Income (ONS estimate)	.011	.000	.058	26.729	.000	.922	1.084
Workplace Employment Special. 2 (Professional %)	-.120	.008	-.049	-14.610	.000	.392	2.551

G.2   Travel Distance Regression Analyses

Table G.6: Interaction Ward Mode-Choice Models Goodness-of-Fit

Model Number	Dependent Variable	Independent Variables Excluded	Weighting Variable	R	R Square	Adjusted R Square	Std. Error of the Estimate
4	Journey-to-Work Ward Interaction Network Distance Weighted Mean (km)	Car Ownership	Flow magnitude	.752[j]	.566	.566	46.75

Table G.7: Model 4 Coefficients

Variables	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics	
	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
(Constant)	-60593.223	618.754		-97.928	.000		
Workplace Commercial Rental Value (VOA estimate)	10.773	.535	.095	20.122	.000	.419	2.389
Residence Accessibility to Population (PT, x=1.7)	-2.049	.018	-.717	-116.807	.000	.248	4.037
Workplace Accessibility to Employment (PT, x=1.7, log)	9856.900	94.768	.861	104.011	.000	.136	7.344
Flow Employment Special. 2 (Professional %)	7178.335	220.337	.164	32.579	.000	.367	2.726
Workplace Air Transport Function (%)	161.742	4.176	.121	38.735	.000	.964	1.037
Residence Household Income (ONS estimate)	-6.463	.189	-.119	-34.145	.000	.770	1.298
Flow Couple Household (%)	6383.678	269.056	.095	23.726	.000	.580	1.724
Employment Special. 1 (Management %)	8136.608	408.453	.089	19.921	.000	.471	2.122
Residence Activity Density (log)	-698.295	41.594	-.114	-16.788	.000	.202	4.957
Workplace Activity Density (log)	-597.209	36.535	-.077	-16.346	.000	.423	2.364

G.3   CO2 Emissions Regression Analyses

Table G.8: Interaction Ward Mode-Choice Models Goodness-of-Fit

Model Number	Dependent Variable	Independent Variables Excluded	Weighting Variable	R	R Square	Adjusted R Square	Std. Error of the Estimate
5	Mean Journey to Work CO2 Emissions by Ward Interaction	Car Ownership	Flow magnitude	.910[b]	.827	.827	3259.29
6	Mean Journey to Work CO2 Emissions by Ward Interaction	Car Ownership, Absolute trip cost variables	Flow magnitude	.718[k]	.515	.515	5462.63
7	Mean Journey to Work CO2 Emissions by Ward Interaction	Car Ownership, all trip cost variables	Flow magnitude	.635[j]	.404	.403	6058.85

Table G.9: Model 5 Coefficients

Variables	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics	
	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
(Constant)	-210.92	3.4651		-60.870	.000		
Flow Distance by Car	.082324	.000198	.803	416.096	.000	.997	1.003
Relative Accessibility Car vs. Public Transport (mins faster by car)	27.487	.11230	.472	244.764	.000	.997	1.003

Table G.10: Model 6 Coefficients

Variables	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics	
	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
(Constant)	-5069.303	81.491		-62.207	.000		
Relative Accessibility Car vs. Public Transport (mins faster by car)	30.357	.29343	.522	103.459	.000	.410	2.437
Workplace Accessibility to Employment (PT, x=1.7, log)	747.402	11.421	.591	65.443	.000	.128	7.810
Residence Accessibility to Population (PT, x=1.7)	-.131627	.00205	-.417	-64.134	.000	.247	4.048
Flow Employment Special. 2 (Professional %)	1112.8	25.881	.230	42.995	.000	.363	2.754
Workplace Air Transport Function (%)	21.725	.49558	.146	43.837	.000	.935	1.070
Residence Household Income (ONS estimate)	-1.0558	.022121	-.176	-47.727	.000	.770	1.298
Flow Couple Household (%)	878.892	31.443	.119	27.951	.000	.580	1.724
Employment Special. 1 (Management %)	923.07	47.753	.091	19.330	.000	.471	2.124
Workplace Activity Density (log)	-45.762	4.4289	-.053	-10.333	.000	.393	2.544
Residence Activity Density (log)	-46.766	4.8987	-.069	-9.547	.000	.199	5.035
Workplace Commercial Rental Value (VOA estimate)	.27086	.06261	.022	4.326	.000	.418	2.393

Table G.11: Model 7 Coefficients

Variables	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics	
	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
(Constant)	-1180.82	80.198		-14.724	.000		
Workplace Activity Density (log)	-167.629	4.7353	-.195	-35.400	.000	.423	2.364
Flow Employment Special. 2 (Professional %)	1383.92	28.558	.287	48.460	.000	.367	2.726
Residence Accessibility to Population (PT, x=1.7)	-.14277	.002273	-.452	-62.805	.000	.248	4.037
Workplace Air Transport Function (%)	30.689	.54121	.207	56.705	.000	.964	1.037
Workplace Accessibility to Employment (PT, x=1.7, log)	458.65	12.283	.362	37.340	.000	.136	7.344
Residence Household Income (ONS estimate)	-1.0815	.024534	-.180	-44.081	.000	.770	1.298
Flow Couple Household (%)	919.02	34.873	.124	26.354	.000	.580	1.724
Employment Special. 1 (Management %)	1076.648	52.940	.106	20.337	.000	.471	2.122
Residence Activity Density (log)	-109.85	5.3911	-.162	-20.377	.000	.202	4.957
Workplace Commercial Rental Value (VOA estimate)	.52034	.069394	.042	7.498	.000	.419	2.389