Exploring the Spatial Implications of Capacity Constraints in Public Transportation Systems: A Scenario-Based Analysis of London

by

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Abstract

In growing regions with large public transportation systems, the distribution of available capacity can affect where development occurs and determine which users and land uses suffer from further crowding. However, analyzing the spatial relationship between available capacity and economic impacts may not be straightforward, and common modeling practice can bias results. Improved modeling practice that more realistically includes capacity and crowding effects has the potential to better predict the benefits of new transportation investments and land use densification strategies.

A series of conventional and innovative techniques, based on static assignment, is applied in three planning scenarios to explore the spatial distribution of disbenefits from crowding in London's public transportation system. The featured scenario examines the crowding relief on existing commuter lines from the opening of a parallel high-speed rail (HSR) line. A sketch assignment model is developed in TransCAD to demonstrate the potential of common modeling practice to bias travel cost estimates, thereby distorting economic predictions.

Conventional methods for enforcing capacity constraint, such as controlling vehicle loading through a link-based penalty, are shown to bias predictions of which users and land uses suffer from crowding. Second, the organized application of select link analysis is found to contribute to a better understanding of which transportation investments and land uses exacerbate crowding problems and which transportation facilities and land uses are vulnerable to crowding problems. Finally, the proposed high-speed rail line is found to reduce crowding on existing commuter lines, thereby improving the development potential of adjacent land uses.

This research aims to highlight certain aspects of the spatial relationship between capacity constraints and economic impacts in large public transportation systems. However, further model refinements, sensitivity tests, and empirical validation are needed to substantiate the initial findings. This research explores only a subset of the potential service challenges from crowding. An enhanced static assignment model or dynamic assignment model could be applied to model these omitted service challenges and develop more robust conclusions.

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1 INTRODUCTION

Effective transportation planning in growing cities and regions requires a clear understanding of system capacity constraints. An underinvestment in capacity could limit access to productive urban centers and constrain economic development. However, our understanding of capacity challenges might be limited by common modeling practices that either minimize the role of transportation in supporting growth or distort the spatial relationship between crowding and economic development impacts.

The static methods[1] commonly used in long-range transportation planning to predict network flows and level of service, the key data for assessing capacity challenges, often include a number of simplifications to reduce data requirements and processing time. Because of these simplifications, the full range of user responses to crowding cannot easily be represented. In some cases, crowding effects could be ascribed to the wrong users or land uses. Static models also tend to minimize the supply-side consequences of crowding, such as irregularities in service.

Dynamic assignment methods can overcome some of the limitations of static assignment, but these methods may require longer computing time, especially for large public transportation (PT) systems, and may be impractical for answering certain policy questions (Dft, 2014c[2]). The challenge is then to determine which policy questions can be satisfactorily answered through static assignment methods, including innovations to static methods, and which policy questions require dynamic assignment.

Research on capacity investments can benefit from a better understanding of the spatial relationship between capacity and economic impacts and from better insights into the contributions and limitations of existing models. This thesis is focused on the practical application of static methods to assess long-term capacity constraints in public transportation systems.

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[1] For simplicity, in this research, "static" assignment generally refers to frequency-based approaches that cannot explicitly represent user departure time or vehicle movement and "dynamic" assignment generally refers to schedule-based approaches that can represent user departure time and vehicle movement. However, it is not correct to assume that all dynamic methods are schedule-based. For example, Schmöcker et al. (2008) proposed a "quasi-dynamic" frequency-based model, while Liu et al. (2010) review some of the distinctions between static and dynamic approaches.

[2] This report contains public sector information licensed under the Open Government Licence v2.0. This license applies to all other DfT references in this research.

Three main objectives have guided this research:

1. Emphasize the importance of the capacity constraint problem by showing how underinvestment in public transportation could harm growing cities and regions;
2. Investigate how errors in enforcing capacity constraints may distort the planning process and lead to inefficient investment decisions;
3. Present methods for exploring how transport capacity can constrain or influence economic growth thanks to a better understanding of accessibility[3] effects and spatial relationships between capacity constraints and economic impacts.

This research focuses on vehicle loading capacity, however there is some discussion of how constraints on vehicle frequency could limit regional accessibility, irrespective of vehicle loading problems. This research is conducted in the context of a growing London that must decide how to advocate for strategic investments. One specific and important issue is how London should condition its support for a proposed high-speed rail project, called HS2, and how it should build support for complementary investments.

The remainder of this chapter is divided into six sections. The first three sections focus on the topic of capacity constraint:

1. The first section describes how static assignment could lead to inaccurate predictions of level of service and distort the spatial relationship between crowding challenges and economic impacts, thereby biasing subsequent capital investment and land use analysis;
2. The second section describes how errors in enforcing transportation capacity constraint in models can distort cost benefit analysis;
3. The third section introduces the concept of capacity-constrained accessibility, which could prove critical for project evaluation and land use strategy evaluation.

The remaining three sections are organized as follows:

4. The fourth section introduces the London and UK research context;
5. The fifth section enumerates the research questions examined in this thesis;
6. The sixth section describes the content of chapters two through nine.

[3] Accessibility is formally defined in Chapter 2

1.1 Capacity Constraint and Static Transit Assignment

A simple approach to determine whether a public transport system can meet expected growth is to initially assume that there are no capacity constraints, assign trips to the network, and then check whether any vehicles are overloaded. Because more people cannot board a vehicle than its capacity, a transportation planner might conclude that some (unconstrained) growth will not occur without further capacity investment.

However, this method does not reflect reality, as some public transport users would adapt to crowded conditions by:

- Changing path,
- Changing mode,
- Travelling earlier or later,
- Not Traveling.

In the long-term, crowding could even factor into a commuter's choice of residence or mode. However, static assignment models tend to rely on adjustments in path to model user response to crowding.

In static assignment, negative effects from crowding are often represented through the use of growing, link-based[4] penalties that are a function of abstract volume to capacity (V/C) ratios[5]. As V/C increases, but remains less than one, the assignment model will apply an increasing penalty that might be thought to represent some combination of:

- Growing discomfort from crowded vehicles,
- Increased dwell times at stations.

Traditional V/C ratio approaches are not particularly sophisticated. In fact, many static assignment models will actually allow the V/C ratio to exceed one, while allowing the link-based penalty to grow at an exponential ratio. However, the exponent used could vary considerably from model to model, with some models allowing the V/C ratio to exceed one by a considerable amount. If the modeling

[4] Link-based penalties apply to all users who traverse that link, regardless of whether they were already on the vehicle or just boarded

[5] A volume to capacity (V/C) ratio is the quotient of the number of people on board the vehicle and the maximum vehicle capacity.

capabilities are available, a more appropriate way to represent maximum loading is through modeling denied boardings.

When denied boardings are modeled, maximum vehicle loading is enforced by restricting the ability of new users to board a vehicle *after* it has become full. However, the alternative, link-based approach, enforces maximum vehicle loading by applying an arbitrarily large penalty so that enough users who boarded at an upstream station, when the vehicle was not full, would consider picking a different path.

An alternative way to explicitly modeling denied boardings, is to apply an increasing stop-based boarding penalty,[6] which is the technique employed in this research (see section 2.1.2 for a review of past attempts at using this approach).

Static assignment models can also fail to address crowding problems within stations, even though there are simple techniques, such as access link-based V/C ratio penalties, to represent capacity challenges. While these capacity challenges are relatively easy to model, there is a one-time cost of coding an intricate walk network, as well as the long-term, data management cost of preserving a highly detailed network. Given time constraints, an intricate walk network was not coded in this thesis and no attempt was made to represent:

- Discomfort from crowded platforms,
- Difficulty in moving through the station.

Another important limitation of static assignment is that it cannot easily predict problems with vehicle movements. In fact, crowding on trains leads to longer dwell times, and an eventual drop in service frequency. This thesis research discusses these limitation without explicitly treating them.

1.2 Capacity Constraint and Accessibility

Transportation investments can increase or improve opportunities for people and businesses. Transportation planners typically apply an accessibility measure[7] to study how well people and businesses are connected to (economic) opportunities.

Investment in different transportation modes can shape patterns of accessibility in distinct ways. Auto investment, for instance, may supply a large, initial increase in accessibly, but is vulnerable to a decrease

[6] Stop-based penalties apply only to users who are boarding the vehicle at a given station
[7] See section for a review of accessibility measures 2.2.2

in accessibility from induced congestion. On the other hand, rail accessibility is generally viewed as being more insulated from growth, thus preserving good connections into dense, urban centers. However, even trains have capacity limits, and a growing urban center may require further investments.

A second issue is that accessibility patterns are in flux. Households and businesses may change location in response to improved opportunities. Population growth may lead to network congestion and reduce access to opportunities. Therefore, a single snapshot of accessibility, before and after an investment, can be misleading. To provide a clear understanding of the spatial relationship between capacity constraints and economic impacts, a range of demand inputs should be tested, varying the total amount and spatial distribution of growth. Changes in accessibility should also be measured in small time increments, starting from the base year, so that capacity challenges can affect growth in as early a scenario year as possible. This step-by-step approach to measuring accessibility would better reflect how and when both travelers and land use investors would perceive constraints.

1.3 Capacity Constraint and Economic Analysis

The way capacity constraints and crowding effects are modeled can influence economic analysis in several ways. There is a growing body literature that recognizes agglomeration, or productivity, benefits that are generated by the spatial concentration of certain types of economic activity (e.g., Duranton and Puga, 2004; Venables, 2007; Graham, 2007). To the extent that investments in transportation capacity can facilitate this concentration of economic activity, there can be large productivity benefits to society from continued investment. Therefore, a failure to properly model capacity constraint and crowding effects could distort economic predictions.

Agglomeration theory is particularly relevant for decisions surrounding investment in public transportation, which can support high density development (Pushkarev & Zupan, 1977; Peralta-Quirós, 2013). While transit advocates, particularly heavy rail advocates, may correctly cite capacity as one advantage over highway investment, there is still a limit to how much capacity a public transport project can actually deliver. If this limit is not properly understood or enforced in modeling, then there could be a systematic underinvestment in transit.

1.4 Background: Growth in the UK and London

The population of London is expected to grow from 7.8 million in 2011 to 8.8 million by 2031 (GLA, 2011), while the population of the UK is expected to grow from 62.3 million in 2010 to 71.4 million in 2030 (DfT, 2013b). Meanwhile, the London Underground is already facing crowding challenges. According to a London Assembly study (2009), Victorian and Northern Line services are already loaded to "maximal" conditions in the AM peak (see Figure 1-1). Inter-city services may also face substantial stress in the future as experts have predicted "high capacity pressure" on critical north-south lines, including the West Coast Main Line (WCML) and East Coast Main Line (ECML), heading into key London stations (Dft, 2013b; see Figure 1-2).

There is also a growing recognition of a wealth and productivity divide in the UK, with 2011 per capita productivity reaching about 27,000 pounds in Greater South-East England, but remaining at about 17,500 pounds in Central and Northwest England (DfT, 2013b). One strategic goal is to pursue public investment, including transportation investment, that could help the rest of the UK become more productive. At the same time, a thriving London may be a buoyant force on the rest of the economy.

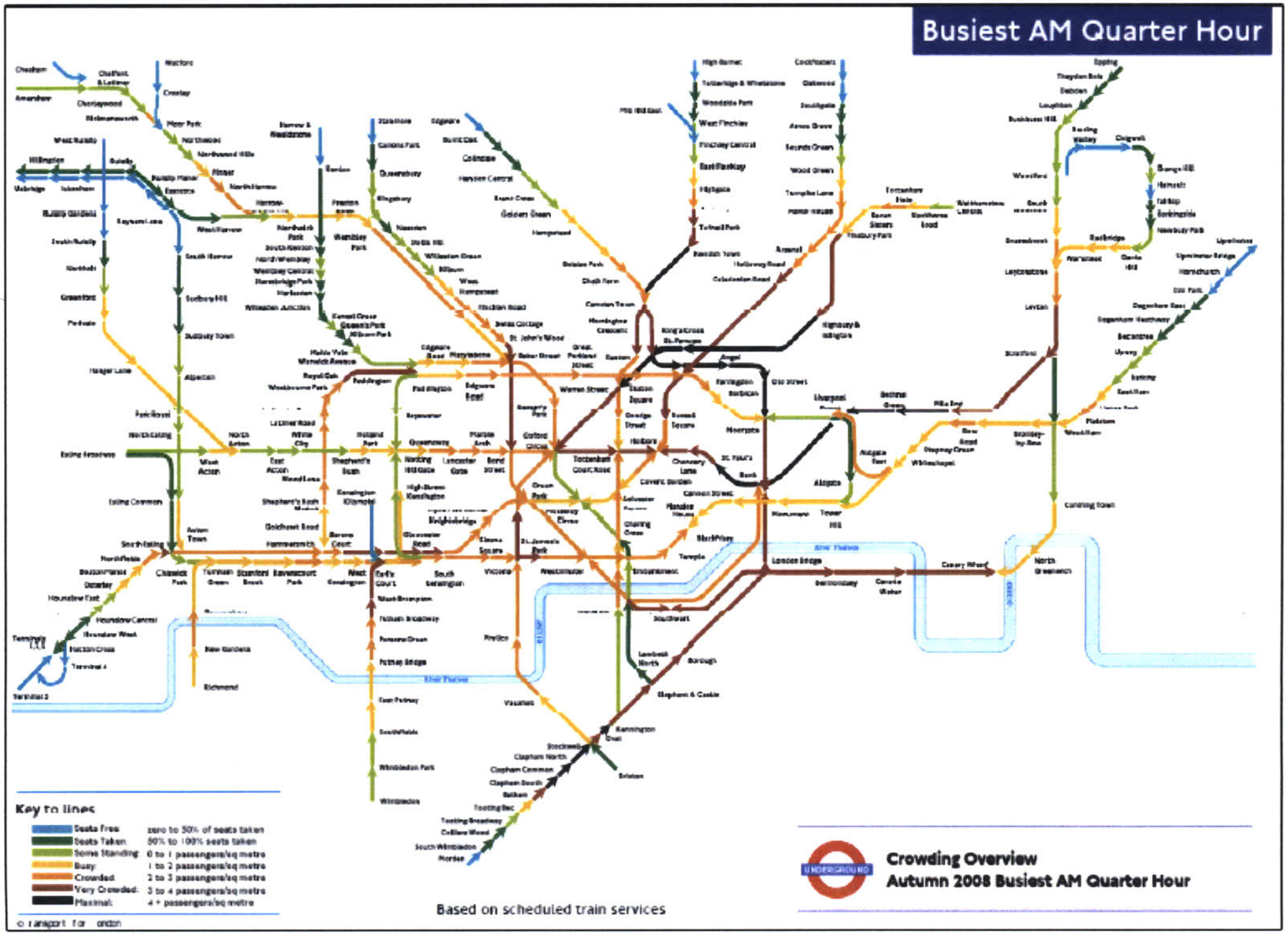
The Department for Transport is planning a new high-speed rail (HSR) line, named High Speed 2 (HS2), that could potentially improve economic conditions in northern Great Britain, as well as in London (DfT, 2013b). The proposed HS2 project (see Figure 3-1) would run from London to Birmingham, and then fork at Birmingham with one branch extending to Leeds and the second branch extending to Manchester.

The HS2 proposal includes two stations in London: a station at Euston and a station at Old Oak Common (see Figure B-3). Euston Station is the current WCML terminus in London, and would act as a central London node. However, Euston Station faces high crowding levels, and some of the Underground lines that HS2 passengers could (potentially) transfer to, such as to the Victoria Line and Northern Line, are already facing capacity challenges, more than two decades before HS2 will completed (see Figure 1-1)

Old Oak Common is located outside of central London, but would have an immediate transfer point to Crossrail services (see Figure B-4) that head to central London, Stratford, and Canary Wharf in the eastbound direction, and head to Heathrow, and other smaller market, in the westbound direction.

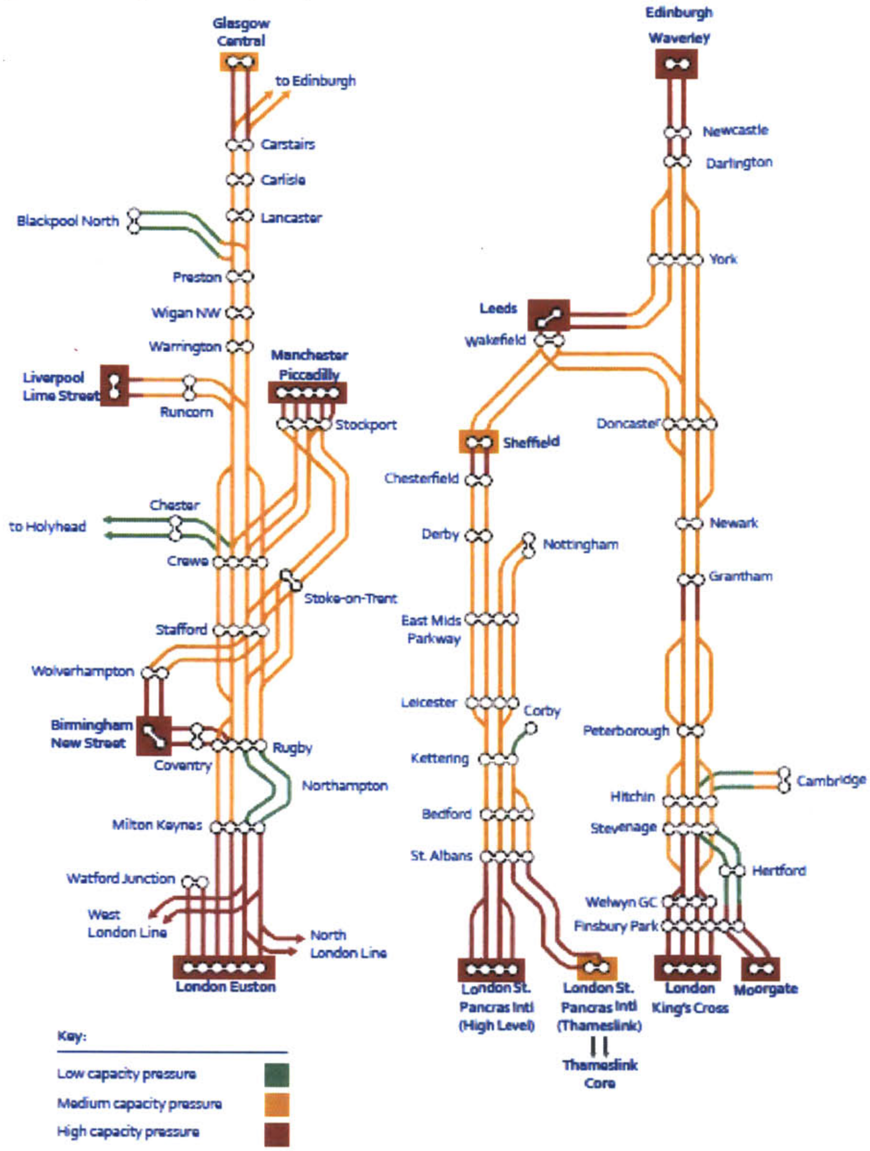
Transport for London (TfL), under the direction of Mayor, Boris Johnson, is considering how the HS2 project could be enhanced to improve benefits for London and surrounding commuter towns. TfL is simultaneously evaluating a new north-south, high-frequency line, tentatively named Crossrail II, that could ease significant crowding challenging within London's Underground and facilitate the onward dispersal of HS2 passengers (London First, 2014).

Figure 1-1: Tube Crowding



Source: (London Assembly, 2009)

Figure 1-2: Expected Capacity Pressure on North-South Main Lines



Sources: (DfT, 2013b; Steer Davies Gleave)

1.5 Research Questions

This section enumerates a series of questions that have guided this research. The questions are divided into four groups.

Policy Questions on Capacity Constraints and Economic Impacts

- How can capacity constraints in large, public transportation systems affect the regional economy? Could capacity constraint affect developer, business, or household decisions?
- Do capacity constraints appear in cost benefit (or economic) analysis? Is capacity constraint appropriately represented?

Questions on Measuring Capacity Constraint

- What methods are most effective for analyzing capacity constraints?
- Can we determine which trips and land uses contribute to crowding problems? Can we predict which trips and land uses are more vulnerable to crowding problems?
- Can we improve our understanding of the relationship among capacity, crowding, and land uses impacts? Is our understanding biased by common modeling practices, such as link-based crowding penalties?

General London Planning Questions

- What capacity challenges might London face in the future?
- Which trips and land uses are more vulnerable to crowding challenges? Could any of the potential development sites in London suffer from public transportation crowding problems?

HS2 Questions

- Is the HS2 project capable of relaxing crowding on existing commuter lines? Which, if any, land uses will benefit?
- Which are the capacity challenges facing Euston Station? Will conditions deteriorate or improve from the HS2 project? How can the WCML Extension improve crowding conditions?
- What impact would the new Crossrail station have on Old Oak Common's development potential? How might Old Oak Common benefit from a new Overground station?

1.6 Thesis Organization

This research is organized into nine chapter including the introduction.

The second chapter reviews the key topics discussed in this thesis: transit assignment, capacity constraint and crowding; cost benefit analysis, wider economic impacts, and agglomeration; and accessibility and the transportation and land use relationship. Given the great breadth and richness of these topics, only a partial review of the literature is presented, emphasizing the sub-topics that are most relevant to this research. When possible, the reader is directed to other authors who have written extensively on a particular sub-topic.

The third chapter reviews the London planning context. This chapter briefly discusses the recent Crossrail business case, which was a successful effort in the UK to include agglomeration benefits in cost benefit analysis. The chapter then discusses some of transportation issues due to London's growth and its emerging development sites. Finally, the chapter discusses the HS2 business case, and its proposed complementary investments.

The fourth chapter presents the author's hypotheses for how public transport capacity challenges could affect economic potential. A framework is developed for exploring which trips and land uses exacerbate crowding problems and which trips and land uses are vulnerable to crowding.

The fifth chapter presents the data and models used in the analyses.

The sixth chapter presents a series of methods to analyze capacity constraints and to explore the spatial relationship between crowding and economic impacts. This chapter also examines a 2041[8] No Build scenario. The No Build scenario establishes a baseline for evaluating the HS2 investment project and complementary schemes.

The seventh chapter explores how errors in enforcing capacity constraint could bias economic analysis. The No Build scenario is compared to a scenario without capacity constraints and to another scenario where crowding effects are modeled without a boarding penalty.

The eighth chapter examines the crowding benefits from the HS2 project to the commuter, and the impact of the proposed West Coast Main Line extension and new Overground station. Only a subset of project

[8] 2041 is 30 years after the base planning scenario, 2011, which is the year of the latest UK census

benefits are modeled, given time and resource constraints, but a discussion on other potential benefits is included.

The ninth chapter reviews the major research findings and discusses their limitations. This chapter also presents ideas for future areas of research.

2 RESEARCH CONCEPTS

This chapter briefly reviews the major topics discussed in this research:

- Transit assignment, capacity constraint, and crowding;
- Accessibility and the transportation and land use relationship;
- Agglomeration and limits to spatial concentration;
- Economic evaluation.

Where possible, the reader is directed to other authors who have written extensively on a particular topic. This chapter is divided into four sections:

1. The first section reviews transit assignment methods, capacity constraint, and crowding.
2. The second section reviews the concept of accessibility.
3. The third section is about the spatial concentration of economic activity. It briefly reviews agglomeration theory, a centripetal force promoting spatial concentration; reviews the relationship between public transport capacity and density; and reviews some planning studies, including Crossrail, that have examined how public transport capacity can encourage growth.
4. The fourth section reviews economic appraisal methods and agglomeration benefits.

2.1 Transit Assignment

This section reviews the transit assignment process and includes a discussion of path choice, capacity constraint, and crowding. A brief discussion of transit assignment's role in the four-step process is also included.

2.1.1 Overview

The main objective of transit assignment is to predict the path choice of public transport users traveling from a fixed origin to a fixed destination[9]. The predicted path choice, which may be a deterministic or probabilistic choice, can be used to estimate the cost of traveling between the given origin-destination pair. A number of factors[10] are recognized to affect path choice, such as:

- Vehicle speeds and travel times,

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[9] Dynamic assignment methods may also consider the departure time of public transport users

[10] These factors, as well as others, are reviewed by DfT (2014c).

- Wait times at stops,
- Walk times to and from stops,
- Crowding levels in vehicles and in stations,
- Fares,
- Travel reliability and user aversion to arriving late or early,
- User knowledge of the system,
- Other User perceptions and biases,
- Distance,
- Departure Time,
- Station or stop amenities.

How each of these factors is represented in the model, if at all, depends on the assignment algorithm used. For example, some algorithms use a constant vehicle travel time, while others algorithms vary travel times based on predicted dwell times at stops. Dynamic assignment or simulation methods can represent vehicle movements explicitly. These path choice factors can be treated as deterministic variables or stochastic variables.

The appropriate algorithm to employ depends on the specific planning context. DfT (2014c) reviews some of the key considerations, including:

- The scale of the network,
- The amount of crowding or likelihood of capacity challenges,
- Vehicle Frequency,
- Service punctuality,
- The amount of heterogeneity in user preferences.

Frequency and Schedule-Based methods

Transit assignment algorithms are either frequency-based or schedule-based. Frequency-based methods rely on average headways and service conditions and are generally simpler than schedule-based methods, requiring less processing when applied to large networks. However, frequency-based models may not be able to explicitly represent certain path choice factors, such as vehicle reliably.

If there is likely to be significant variance in when passengers and vehicles arrive during the model period[11], then frequency-based methods could introduce significant biases. In reality, even if the "average" capacity is enough to meet the "average" demand, the stochastic nature of passenger and vehicle arrivals could lead to denied boardings. However, the risk of introducing a major bias from applying "average" conditions can be minimized by assigning multiple, short periods, perhaps 15 minutes in length, where service conditions are relatively homogenous. For example, Schmöcker et al. (2008) proposed a "quasi-dynamic" frequency-based model that can represent fail to board probability within small time intervals.

Schedule-based models can represent the actual temporal distribution of passenger and vehicle arrivals within the model period. These models may be more appropriate for representing the dynamics of supply and demand and variance in service (Dft, 2014c).

Path Choice

The extent to which a path choice model can represent multiple path choices between each origin and destination is an important and distinguishing feature. In best-path assignment, demand is loaded onto the minimum cost path, or hyperpath, between origin-destination pairs (DftT, 2014c).

The best-path approach can assume that users do not have perfect knowledge of vehicle arrival times, and employ strategies (Spiess and Florian, 1989) for selecting which vehicles to board. If crowding effects are modeled, the initial loading is unlikely to result in a deterministic equilibrium that obeys Wardrop's (1952) first principle: no user can improve his travel time by switching paths. The model is then run in an iterative manner until a reasonable level of convergence has been achieved. During the iterative process, different paths can be selected, and the final result will represent some weighted combination of each chosen path.

Discrete path choice, based on the principles of random utility theory (see Ben-Akiva and Lerman, 1985), is one approach to incorporate a significant, multi-path element to transit assignment. It is assumed that users have unobserved heterogeneity in taste. Therefore, the lowest-cost path for one user may not be the lowest-cost path for another user, and a probabilistic description of path choice is required.

[11] It is common to use a peak hour or peak period as the key assignment period.

Path choice in dynamic assignment can also include a temporal component, where users can choose a departure time. Liu et al. (2010) review the principles of path choice in dynamic assignment and discuss emerging techniques.

2.1.2 Capacity Constraint

The earliest assignment models, such as in Dial (1967) did not represent capacity constraint. The first model to try to address capacity constraint is the TRANSEPT model (Last and Leak, 1976). De Cea and Fernandez (1993) showed that the TRANSEPT is only appropriate for radial routes. De Cea and Fernandez developed the first version of the "effective frequency" approach. Further contributions are made in Cominetti and Correa (2001) and Cepeda et al. (2006).

The effective frequency approach is a class of assignment methods that applies a growing wait time penalty at stops based on the number of boarding passengers, capacity after boarding, and vehicle frequency. The method cannot explicitly represent capacity constraint, but can introduce a practical constraint on ridership by growing the wait time arbitrarily large. Another criticism of the approach is that the wait time grows continuously (DfT 2014c). In reality, the experienced wait time would grow as a step function, with users having to wait another headway if they miss a vehicle. On the other hand, what affects path choice strategies is an expectation of wait time, which could grow in a continuous manner and not as a step-function.

The effective headway approach has been applied to a number of transportation planning models. Florian et al. tested versions in Winnipeg, Stockholm, and Santiago (2005). SKM developed an alternative assignment algorithm, called CAPSTRAS for London's Railplan model (Maier, 2011). The wait penalty in CAPSTRAS is defined as:

$$\frac{headway}{1-\left(\frac{boardings}{residudal\ capacity}\right)^{beta}}$$

More sophisticated, but generally slower, methods exists to explicitly treat capacity constraint within frequency-based or schedule-based assignment. For example, see Schmöcker et al. (2008), Nuzzolo et al. (2012), and Hamdouch et al. (2011).

Given the scale of the London network and project time and resource constraints, this research focused on the "practical" application of capacity constraint in frequency-based assignment, achieved through a growing stop-based penalty. A very sophisticated treatment of capacity constraint would have required explicitly representing denied boardings in scheduled-based assignment.

2.1.3 Representation of Crowding

Discomfort from traveling in crowded vehicles is one potential impediment to travel. However, discomfort is a perceived effect and the disutility from riding in crowded vehicles could vary substantially across users. For instance, a revealed preference experiment of people boarding the Victoria Line at Seven Sister's Station found that some passengers are willing to wait an extra headway to board an uncrowded train instead of a crowded one (Railplan, 2006).

Wardman and Whelan (2010) reviewed evidence from the British Experience. The evidence was mixed and varied across studies, partially based on how crowded conditions were defined. The average travel time multiplier for standing in crowded conditions was 2.32 and the average multiplier for being seated in crowded conditions was 1.19. A study by MVA Consultancy (2008) estimated travel time multipliers as a function of the number of standing passengers per meter squared.

Figure 2-1: Crowding Multipliers

	Non-business		Business		LSE		Regional		Interurban	
Pass./m^2	Sit	Stand	Sit	Stand	Sit	Stand	Sit	Stand	Sit	Stand
0	1.00	1.48	1.00	1.91	1.00	1.43	1.00	1.34	1.00	1.77
1	1.10	1.58	1.13	1.95	1.09	1.56	1.24	1.61	1.11	1.81
2	1.21	1.68	1.27	1.99	1.18	1.69	1.48	1.88	1.23	1.85
3	1.31	1.77	1.40	2.03	1.27	1.82	1.72	2.16	1.34	1.89
4	1.41	1.87	1.54	2.08	1.36	1.95	1.96	2.43	1.46	1.92
5	1.52	1.97	1.67	2.12	1.45	2.08	2.20	2.70	1.57	1.96
6	1.62	2.06	1.81	2.16	1.54	2.21	2.44	2.97	1.69	2.00

Source: (MVA, 2008; Wardman, 2010)

Discomfort from traveling in crowd vehicles is generally represented by factoring travel time. For example, the multipliers in Figure 2-1 could be used to weight travel times. However, crowding in public transport systems can affect service in other ways:

- Increased discomfort from standing on platforms or difficulty moving through stations;
- Increased probability of denied boardings;

- Increased vehicle dwell times, potentially leading to service irregularities and a decrease in maximum vehicle frequency

2.1.4 Role in Four-Step Model

Trip assignment is the final step in the classic, four-step modeling process[12]. While biases in the transit assignment step itself can lead to poor predictions of path choice and vehicle loading, the other steps are obviously critical for generating reasonable forecasts. For example, no transit assignment algorithm can fix fundamental flaws in the trip generation step.[13]

In trip generation, socioeconomic data, such as the number and location of households, are used to derive zonal estimates and how many trips are "produced" each day. Other socioeconomic data, such as the number and location of businesses, are used to independently predict how many trips are "attracted" each day to a particular zone. The trip total productions and attractions in the region are balanced according to some set of rules, based on the relative confidence of production and attraction rates.

Poor estimates of trip productions or trip attractions leads to poor results in transit assignment. However, the quality of the trip generation estimates is constrained by the quality of the available socioeconomic data.

Trip distribution is generally the second step, although its relationship with the mode choice step can vary from model to model. In trip distribution, the initial estimates of productions and attractions, together with assumed impedance functions per mode, are used to construct a demand matrix that represents flow between every zone pair. The trip distribution step can bias assignment results by over or under-estimating trip length or distorting which OD pairs are generating the most trips.

Mode choice, generally the third step, results in the demand matrix being segmented by mode, usually through a discrete choice model. Of course, the mode choice step has significant potential to bias transit result. A poor representation of the relatives attractiveness of taking transit versus driving can bias predictions of the number of "choice" riders, while a poor representation of income levels and automobile ownership rates can bias predictions of the number of "captive" riders.

After the initial highway or transit assignment, it is customary to "feed" the assignment results back into the four-step model, and repeat the entire process with updated assumptions. In sophisticated models,

[12] This review of the four-step model is based primarily on the author's professional judgment

[13] Although, the transit assignment step can be used, in part, to flag potential mistakes in trip generation

the assignment results could be used to adjust the original socioeconomic assumptions. For example, the model could either redistribute or reduce growth to increase the likelihood that volume to capacity ratios will be less than one in the next assignment iteration.

2.2 Accessibility

Accessibility is an important concept in transportation planning and has a number of applications ranging from equity analysis to land use forecasting and economic evaluation. Accessibility measures can reveal how transportation impacts the number and quality of opportunities for residents and businesses and illuminate the transportation and land uses relationship.

Hansen (1959) is attributed with providing the initial definition of accessibility as the "potential of opportunities for interactions." Other useful definitions are given by Wachs and Kumaga (1973) who defined accessibility as "the ease with which any land-use activity can be reached from a location using a particular transport system," Ben-Akiva and Lerman (1985) who defined accessibility as, "the benefits provided by a transportation/land-use system," and Geurs and van Week (2004) who defined accessibility as, "indicators for the impact of land-use and transport developments and policy plans on the functioning of the society in general."

Early work on accessibility is summarized in Bhat et al. (2000) and in Guers and van Eck (2001). Synthesizing past work, Guers and van Wee (2004) present a framework for understanding the components of accessibility and types of measures.

Following the work of Geurs and van Wee, this section beings by reviewing the various components (see section 2.2.1) and measures (see section 2.2.2).

This research builds on a series of past accessibility studies by MIT students including: Busby (2004), Warade (2007), Ducas (2011), and Peralta-Quirós (2013). Where possible, this research frames the discussion of accessibility in terms of capacity or congestion effects.

2.2.1 Components of Accessibility

Geurs and van Wee (2004) indicate that there are four components to accessibility:

1. Transportation: The transportation component refers to the mode-specific cost of travel from a given origin to a given destination. This component accounts for crowding effects from imbalances in transportation demand and supply.

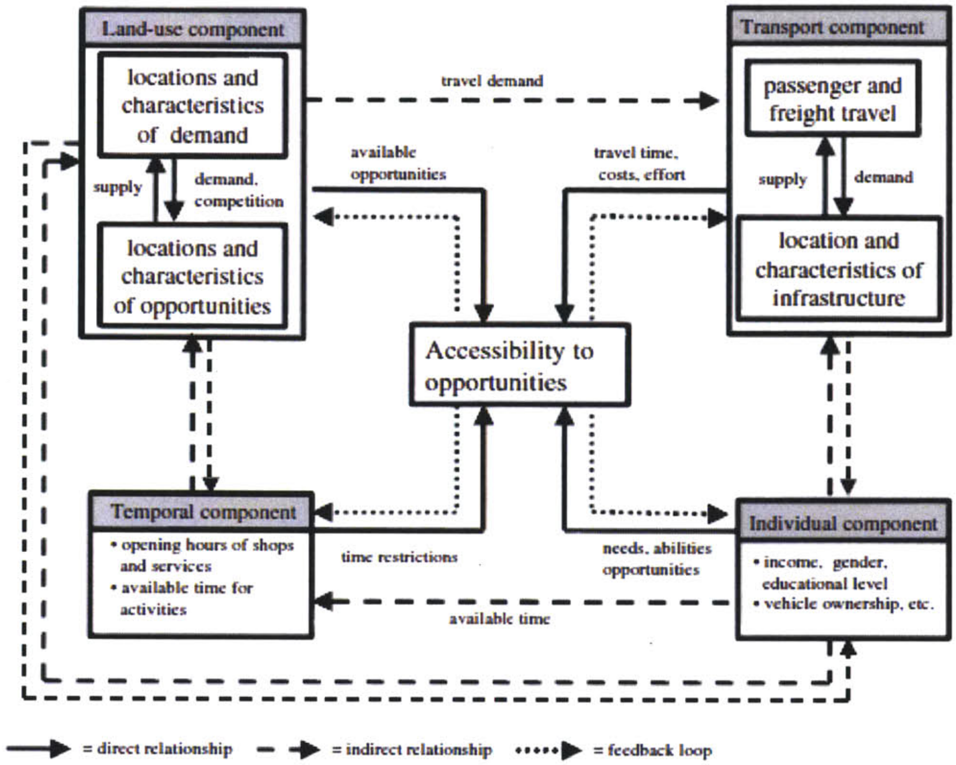
2. Land-Use: The land use component refers to the spatial distribution of the demand and supply of opportunities, where the supply of opportunities consists of jobs, amenities, public goods, etc. and demand consists of households, business, etc. This component accounts for competition effects from imbalances in the demand and supply of opportunities, such as white collar jobs.

3. Temporal: The temporal component refers to any constraints on when opportunities are available, such as when shops are open, and any constraints on when demand can access these opportunities.

4. Individual: The individual component refers to what opportunities are available to individuals based on their socioeconomic characteristics (e.g. income), abilities (e.g. physical condition, education level), and needs (e.g. need for employment). For example, being poorly educated would preclude an individual from many opportunities. An individual's travel time budget or aversion to crowding might preclude him from certain opportunities.

Figure 2-2 presents the components of accessibility and their interactions, which represent the opportunities available to individuals. Investment in public transportation capacity could affect this relationship in several ways. More capacity could decrease the discomfort from crowding or reduce journey times from decreasing vehicle dwell times or reducing the probability of denied boardings. These changes will generally increase the "willingness-to-travel" and make more opportunities available for those on the margin between traveling and not traveling. As discussed further in section 4.1, the capacity investment can affect the land-component by attracting businesses through a reduction in the "wage premium" that businesses need to pay their employees for traveling in crowded condition or through increasing agglomeration economies (Weisbrod, 2009).

Figure 2-2: Components of Accessibility



Source: (Geurs & van Wee, 2004)

2.2.2 Measures of Accessibility

There is no one "correct" measure of accessibility. Some measures cannot represent all the components of accessibility, limiting their theoretical potential (Geurs and van Wee, 2004). However, certain measures with known theoretical limitations, such as unweighted isochrones, may be particularly easy for analysts to interpret or explain to non-technical audiences. Therefore, both the strength and weakness of an accessibility measure can be its degree of sophistication.

A number of measures have been proposed over the past 60 years, and are reviewed by various authors, including Geurs and van Wee (2004), Busby (2004), Warade (2006), and Ducas (2011).

Geurs and van Wee (2004) group accessibility measures into four categories: infrastructure-based measures, location-based measures, person-based measures, and utility based measures.

Infrastructure-based Measures

Infrastructure-based measures describe the transportation component of accessibility and can represent level of service and mobility benefits. For example, infrastructure measures may report statistics such as average vehicle speed or hours of delay. The data requirements for designing infrastructure-based measures are moderate and these measures are less challenging to explain to non-technical audiences. However, infrastructure-based measures do not represent the land-use component of accessibility, which is a significant limitation.

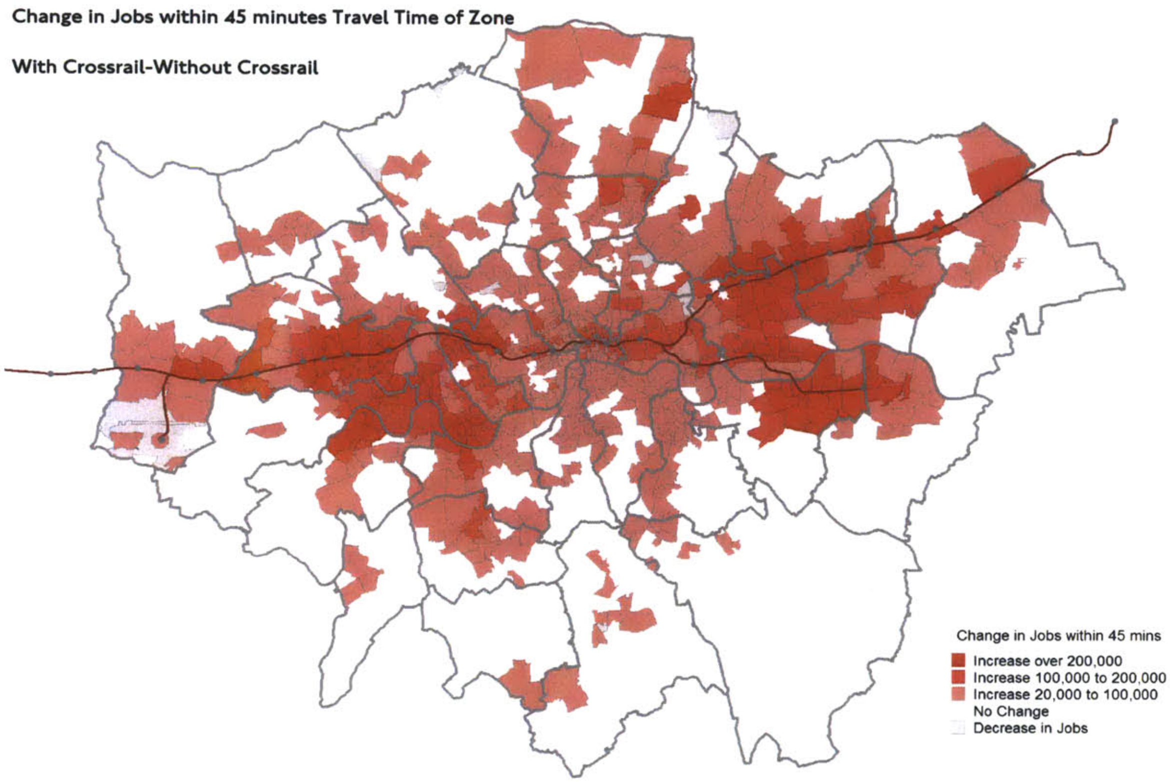
Location-based Measures

Location-based measures are generally applied at an aggregate level to describe the level of access from points in space to surrounding land uses and activities. Location-based measures can represent the land use and transport component of accessibility and partially represent the individual and temporal components. An individual component could partially be represented by developing unique location-based measures for different segments of the population. For example, access to jobs could be measured by income, or value of time,[14] segment. The temporal component can be included through varying the travel and land use data by time of day.

Location-based measures are often used in transportation planning because the data requirements are typically moderate and unlike infrastructure-based measures, they can represent both the land use and transportation component of accessibility. One common location-based travel time measure is the isochrone, which represents the number of opportunities within a travel time threshold (see Busby, 2004). The isochrone measure was used in the Crossrail business case to demonstrate that the project would bring a large number of jobs to within 45 minutes of London residences (see Figure 2-3).

[14] Value of time is discussed in section 2.4.1

Figure 2-3: Isochrone Measure in Crossrail Business Case



Source: (TfL, 2011)

The main advantage of the unweighted isochrone measure is that it is can be used to explain accessibility benefits in simple terms. However, the measure suffers from a number of theoretical limitations. First, impediments to travel besides time, such as crowding and cost, cannot be represented. Second, travel time components that are known to disproportionately affect path choice, such as wait times and walk times, are not assigned extra weight. Finally, the measure includes a cliff-edge effect, where an opportunity is given a weight of one if lies just inside of the travel time threshold, but given a weight of zero it lies just outside of the travel time threshold.

The isochrones measure is also very sensitive to the travel time threshold. For example, if the threshold is set at 60 minutes, two land uses could appear to have a similar level of accessibility, but if the threshold is set at 30 minutes, one land use could appear to have a significantly worse level of accessibility than the other.

The gravity measure, which is another common location measure, attempts to address the threshold problem by giving opportunities a zero through one weight as a function of travel cost (see Busby, 2004).[15] However, while the gravity measure eliminates the cliff-edge effect by weighting opportunities from a continuous function, the weighted opportunities may be difficult to interpret or explain to non-technical audiences.

Person-based Measures

Person-based measures are derived from the pioneering space-time work of Hägerstrand (1970) and are a full disaggregation of accessibility to the individual level. Person-based measures can capture the set of opportunities that are available based on factors such as an individual's location, transportation options, time budget, and needs. Person-based accessibility measures generally possess many theoretical strengths, but have large data needs and require very sophisticated models to be applied in transportation planning.

Utility-based Measures

Utility-based measures incorporate the benefit (utility) that individuals receive from potential access to opportunities. A utility-based measure that is sometimes used in transportation planning, including in the LonLUTI model, is the "logsum" measure, which calculates the expected maximum utility from a transportation choice set. The principles underlying discrete choice analysis are reviewed in Ben-Akiva and Lerman (1985).

The primary advantage of the utility-based measure is that it can directly estimate the benefit (utility) an individual receives from the transportation and land use system, something the isochrone and gravity location-based measures cannot do. However, the logsum measure is challenging to validate, given its welfare implications, and can be difficult to interpret and explain to non-technical audiences.

2.3 Spatial Concentration of Economic Activity

Spatial patterns of economic concentration are determined, in part, from opposing centripetal and centrifugal forces. Glaeser (1998) argues that "the benefits of cities come ultimately from reduced transport costs for goods, people and ideas." These cost reductions tend to agglomerate economic activity. However, the degree of spatial concentration is limited by opposing forces such as increasing land

[15] This research employs the gravity measure to study accessibility patterns. Figure 6-4 shows the weights that were used and Figure 6-5 shows an example application

prices, and rising levels of crowding, pollution, and crime (Glaeser et al., 2001). A reduction in public transportation costs would tend to make jobs more accessible for all, but may benefit captive riders the most.

Section 2.3.1 briefly introduces agglomeration theory, which is one explanation for observed economic concentration. Section 2.3.2 presents some prior research conclusions on what factors ultimately affect household, business, and developer location decisions. Finally, section 2.3.3 discusses how transportation capacity can limit the degree of spatial concentration.

2.3.1 Agglomeration

Agglomeration theory maintains that there are positive returns to scale from the spatial concentration of certain types of economic activity. For physical agglomeration to occur, the productivity benefit from economic concentration needs to outweigh the cost of further crowding.

The early theoretical basis for agglomeration benefits is attributed to Marshal (1890) who described the relationship between economic concentration and improved labor market interactions, interactions between business suppliers, and opportunities for knowledge spillovers. More recently, Duranton and Puga (2004) proposed a new framework for understanding agglomeration benefits in terms of the potential for "sharing", "matching", and "learning." Sharing benefits may arise from the efficient use of inputs and resources and from risk mitigation, given that a large labor market or diverse array of intermediate goods may allow businesses to rapidly adapt to changing conditions. Large labor markets may increase the probability that businesses are matched with suitably skilled workers. Finally, economic concentration may help spread skills and ideas.

A number of studies have examined the relationship between productivity and aggregate measures of agglomeration, such as population, employment, or employment in major sectors of the economy. While these studies generally find a positive relationship between agglomeration and productivity, Melt et al. (2008) noted a wide range of estimates exist that can vary significantly depending on the agglomeration variable used and how quality of labor effects were treated. Graham (2007) found that productivity effects can vary significantly across detailed sectors of the UK economy.

Venables (2007) argued that the induced agglomeration and tax effects from transportation investment could be an important omission from standard cost benefit analysis[16].

A transportation investment could increase agglomeration economics of scale either by facilitating physical concentration or by making the city "effectively" denser. In the UK, Graham (2007) developed an "effective density" measure to analyze the degree of agglomeration. The present version of the effective density measure, as DfT prescribes for use in transportation analysis, resembles the accessibility potential measure (DfT 2014b).

2.3.2 Location Decisions

Transportation investment can affect the level of access to opportunities, such as jobs, amenities, and public goods, thereby influencing household and business location preferences. The market would then react to changes in location preferences by updating land prices and rents, leading towards a new equilibrium.

The value that households and businesses ascribe to different opportunities shapes their location decisions. A successful developer needs an acute understanding of which opportunities matter to household and business, and can benefit from insight into how transportation schemes affect access to these opportunities.

In a guidebook for understanding the transportation and land use relationship, Parsons Brinckerhoff Quade & Douglas, Inc. (1998) enumerated those factors that are most significant in shaping the location decisions of households, businesses, and developers. The guidebook was developed for an American planning context, and the recommendation reflect the dominance of the automobile. However, the recommendations could be adapted for other parts of the world based on the dominant mode of travel. Table 2-1 shows the factors that influence household location decisions. While the level of access to jobs is a significant factor, housing prices are even more important.

Table 2-1 suggests that avoiding heterogeneous, or diverse, communities may be a moderately important consideration for household location choice. This is an important finding because transportation

[16] These agglomeration benefits are considered "external" to traditional cost benefit analysis because they were not considered by past land use developers or current businesses who benefit from the increased economic concentration

investment cannot address this type of social bias. Therefore, in some cases, transportation investment may have limited potential to immediately affect location decisions.

Table 2-1: Factors Affecting Household Location Decisions

Relative Importance	Factor	Comments
Highly Important	Housing costs	Most households must balance costs with the housing and community characteristics they desire.
Moderately Important	Access to jobs	Access to jobs is a significant determinant of residential location in large metropolitan areas, but may not matter in smaller urban areas where nearly every location has good automobile access to jobs.
	Access to goods and services	Preferences vary by household types. Singles like living near entertainment. Empty nesters near leisure and culture. Corporate executives want good access to airports.
	School quality	Important to households with school age children.
	Type of community residents	Although some people like diversity, most people want to live near people who are like them.
Somewhat important	Amenities and quality of life	Households seek locations with views, attractive design, distance from industries and traffic, low crime rates, and other indicators of quality of life.
	Quality of non-school public services	There is some evidence that households consider the quality of public services like police protection when selecting communities.
	Property tax rates	The evidence is mixed on whether taxes matter in household location decisions.

Source: (Parsons Brinckerhoff Quade & Douglas Inc., 1998)

Table 2-2 presents the factors that influence business location decisions. The most important factors are the cost and availably of space, access to labor, access to customers, and access to the dominant mode of travel. While the table indicates that agglomeration benefits are a moderately important consideration, Graham's work (2007) suggests that localization economies of scale can vary significantly across economic sectors.

When choosing where to locate, a business will consider the productivity implications for its own, internal balance sheet. However, a business would not consider the productivity implications for surrounding, or external, businesses. Therefore, a business's location decision might create positive agglomeration externalities, particularly if the business chooses to locate in a dense or productive area. These agglomeration externalities can have large socio-economic benefits and should be counted in cost-benefit analysis.

Table 2-2: Factors Affecting Business Location Decisions

Relative Importance	Factor	Comments
Highly Important	Costs and availability of space	Firms make trade-offs between the cost of space and other locational characteristics that they desire.
	Access to labor	Firms have different labor needs that influence where they locate. Some locate in the CBD to have the greatest access to a high skilled labor force. Some prefer suburban locations where there are stable clerical and support workers. Some locate near residential areas preferred by key technical and managerial staff.
	Access to customers	Critical to retail and customer serving offices. Also important to many manufacturing firms.
	Access to highways	All types of firms need access to the dominant mode of transportation to attract workers and customers and to receive and send deliveries.
Moderately Important	Near like firms	Many firms agglomerate near similar types of firms in retail centers, office parks, industrial parks, and downtowns. This improves their access to workers, customers, and intermediate inputs, and facilitates an exchange of information.
	Near suppliers, support services	This is most important for manufacturers and somewhat important for offices.
Somewhat important	Amenities, quality of life, prestige	This is important for firms with many professional workers and technical workers.
	Quality of public services	Public services are important for business activity and growth. Some manufacturers have specific requirements for large amounts of water and sewer capacity.
	Property tax rates	Manufacturing is most sensitive to local tax rates.
	Access to airport	This is highly important for headquarters or operations of national/global firms.
	Economic development incentives	Incentives are highly important to some firms. They can also influence the amount and location of redevelopment.
	Location of competitors	This is important especially for retailing.

Source: (Parsons Brinckerhoff Quade & Douglas, Inc., 1998)

Table 2-3 enumerates the factors that influence development location decisions. The availably and cost of land and infrastructure are key considerations, as is the accessibility benefits of the location. While cost, availability, and accessibility are important factors for developers, getting appropriate market intelligence from current trends may be the key to profitability.

Table 2-3: Factors Affecting Development Location Decisions

Factor	How Factor Affects Developer's Decisions
Sales and rental prices	Critical determinant of profitability. More desirable locations command higher prices.
Accessibility and visibility	Necessary for retail and most office development. Access to highways important to manufacturing that relies on trucking. More accessible residential locations are more desirable than less accessible locations.
Site characteristics	Can influence both prices and the cost of development.
Growth corridors (e.g. desirable community characteristics)	Development is more likely to occur where there is momentum, but as an area becomes built out or preferences change, these can shift. Developers who correctly anticipate shifts can make more money.
Competition in the market	Profit levels depend upon the competition from existing development and the products that other developers might build.
Land availability and costs	A major factor in deciding what and where it is profitable to build.
Zoning and other regulations	Impacts depend upon whether a community is market-oriented (i.e. adapts regulations to fit with developer proposals) or growth-management oriented (development must fit within plans).
Cost and difficulty of getting permits	Can add to the costs and risks of a project, influencing the type of projects proposed.
Development incentives	Can encourage development where it would not occur without public support, such as redevelopment and infill projects or housing in downtowns.
Availability and cost of infrastructure	Key component of deciding where and what to build.

Source: (Parsons Brinckerhoff Quade & Douglas, Inc., 1998)

2.3.3 Transportation Capacity and Economic Concentration

There have been several studies examining the relationship between transportation capacity and economic concentration. In American cities, Weisbrod and Reno (2007) conclude that a 1% increase in public transportation mode share correlates with an extra 650 person density increase per square mile. However, the authors noted concerns about implying causality as higher densities might "require" public transport service.

A recent study of US cities by Chatman and Noland (2014), which made extensive use of instrumental variables to address causality concerns, found a strong relationship between public transport service and employment density. An increase of 3.66 transit seats per 1000 people was linked to 320 more jobs per square mile in the "central city" area. However, the increase in "central city" employment may be partially offset by lower employment densities found elsewhere in the city. Across US cities, a productivity benefit from a 10 percent increase in transit seats was associated with a range between a $1.5 million to $1.8 billion increase in wages.

Several planning studies have examined how transport capacity could affect the spatial concentration of jobs in business districts. A study of a new LRT system in Tel Aviv found that 40,000 jobs might relocate to the CBD, delivering significant agglomeration benefits (Schefer and Aviram, 2005).

Crossrail Business Case

The Crossrail[17] business case argued that London's transportation system could not accommodate all of the assumed employment growth in central London and Isle of Dogs (TfL, 2011a) and these jobs would have to be located elsewhere to exist at all. The most recent prediction of the number of displaced jobs is shown in Table 2-1.

Table 2-4: Crossrail Crowding Out

Employment Location	Jobs Crowded out (Peak Hour)		
	2016	2026	2075
Central London	4,820	19,017	24,009
Isle of Dogs	4,026	8,168	10,072
Total	8,846	27,185	34,080

Source: (TfL, 2011a)

Two methods were proposed to forecast the number of displaced jobs (Buchanan, 2007). The "cordon capacity" approach[18], which was ultimately adopted in the Crossrail business case, measures the total peak-hour demand going into a zone against the capacity limit. It was assumed that as the cordon capacity of central London or the Isle of Dogs approaches, some forecasted job growth would need to occur elsewhere (see Table 2-5).

[17] See Figure B-4

[18] The cordon capacity approach is reviewed in section 6.3

Table 2-5: Cordon Capacity Crowding Deterrence

$C < 0.84$	No deterrence
$0.84 \le C < 1.49$	An increasing proportion of people are deterred
$C \ge 1.49$	All people deterred

Source: (TfL, 2011a)

The "select link" approach, which was explored by Buchanan (2007) for the Crossrail project, measures the number of trips face various levels of crowding. Two key assumptions were made in interpreting the select link results. First, there is significant variance in how much users dislike crowding. Second, the observed distribution of willingness-to-travel under crowded conditions already reflects the limit of what can be tolerated. For example, the percentage of passengers who are observed to travel at the highest level of crowding indicates the percentage of travelers who would ever be willing to travel at the highest level of crowding. It was then assumed that travel to employment centers in central London and the Isle would be constrained by this distribution of crowding tolerance. Table 2-6 shows the number of unconstrained trips facing different levels of crowding with and without Crossrail.

Table 2-6: Crossrail Select Link Analysis of Crowding

With XR	Total	0.0-0.3	0.3-0.75	0.75-0.8	0.8-1.0	1.0-1.25	1.25-1.5	SL>1.5
Dogs	37,905	60	784	365	6,155	12,695	8,997	7,069
Central	456,086	241	3,832	6,864	22,186	130,265	153,576	90,283
Without XR								
Dogs	37,905	70	34	5	210	13,441	12,382	9,921
Central	456,086	246	2,941	2,321	12,027	66,434	193,066	128,424

Source: (Buchanan, 2007)

2.4 Transportation and Economic Evaluation

This section reviews common methods for economic evaluation and considers the role of capacity constraint in the economic appraisal process. The discussion is centered on micro-economic approaches, particularly the travel time savings approach and recent efforts to address biases in the travel time savings approach.

2.4.1 General Discussion

In evaluating transportation investment, a useful distinction can be drawn between two questions:

- How would the investment impact the economic geography of the region (nation)?
- What is the total benefit of the investment for the region (nation)?

The answer to the second question would, in theory, partially rely on the answer to the first question[19]. However, it is common practice to predict the total benefit to society without explicitly representing the change in economic geography; some change to the trip distribution may be represented, but the long-term implications for the region's economic geography are usually not explored in great detail.

The reason for not taking an in-depth look at change in economics in the area could be due to practical concerns about study cost, data availability, and forecasting reliability. However, there is also a theoretical argument, grounded in the travel time savings paradigm, for foregoing a detailed analysis of impacts on economic geography and non-transportation markets. The logic generally proceeds as follows: travel time savings, combined with other direct user benefits within the transportation market will describe the first order impact of the project. Under the assumption of perfect competition, namely assuming that there are no significant (unmodeled) externalities from transportation investment, the first order impact would yield the true benefit to society (SACTRA, 1999). Through the operation of the market, the benefit of the initial investment could be transferred to other parties or absorbed into land values, but the net benefit to society would remain constant over time.

However, after acknowledging the theoretical basis for the travel time savings paradigm, a 1999 SACTRA report enumerated a number of ways in in which traditional appraisal could be biased from ignoring externalities. As discussed further in section 2.4.3, an important externality that is not captured in the traditional travel time savings methodology is the productivity benefit from agglomeration (e.g. Graham, 2007). There are also other important externalities related to taxes (Venables, 2007).

Along with environmental impacts, a clear externality caused by transportation investment is congestion. When correctly applied to a sufficiently large study area, the travel time savings method explicitly represents the first order of congestion externalities, as well as capturing any congestion effects from changes in the updated, trip distribution matrix. However, the travel time savings method cannot capture congestion externalities from unmodeled changes in economic geography.

Therefore, on one hand, the proper enforcement of capacity constraints in models is needed to understand first order congestion effects. On the other hand, proper enforcement is needed to explore the potential for second order relocation effects and to consider how and when congestion would act as a centrifugal force. Second order relocation effects may be important for shaping the evolution of a

[19] For example, an unbiased representation of the changes in the spatial distribution of growth is needed for an unbiased prediction of congestion

region's economic geography. For example, it is hard to imagine how the significance of the original Metropolitan Line investment to London could be explained by only considering first order effects, and not considering a long chain of events that were enabled through availability public transport services. More recently, the Jubilee Line Extension investment has been recognized for promoting and sustaining growth. TfL's assessment is that the "previously-existing systems would not have been able to cope with the number of passengers who now commute to Canary Wharf on the Jubilee line" (TfL, 2011b).

Basing economic analysis on travel time savings has been criticized for other reasons. One reason is that direct user benefits, such as travel time savings, may be fragile, and may disappear as congestion grows worse or people travel more. In fact, the initial travel time savings may simply induce more travel. It has been observed that the proportion of time and budget people allocate for transportation has been remarkably stable over time (Schafer and Victor, 2000). Given the long-term stability in travel budgets, some might conclude that our understanding of transportation "benefit" is corrupted by a fixation on travel time savings. Casting the benefits in terms of other effects, such as accessibility improvements, may be a more appropriate way to understand the value of transportation investment (e.g. Metz, 2008).

A potential counter-argument is that any perceived misrepresentations of observed behavior can, at least in theory, be addressed through improving transportation models, while still casting benefits in terms of travel time savings. For example, the trip distribution and mode choice steps can be improved to better account for observed responses to changes in accessibility. Improving these steps may leads towards using substantially different trip matrices in the build and no build scenarios. Changes made to the trip matrices in the build scenario would (likely) imply additional agglomeration or productivity benefits that need to be included in cost benefit analysis (see section 2.4.3).

Nevertheless, it remains possible that a fixation on travel time savings could distort how planners and policy makers think about transportation. For example, if project benefits are cast in terms of accessibility changes, then planners and policy makers may be incentivized to think in terms of accessibility.

A second criticism of presenting benefits in terms of travel time savings is that the conclusions may not be compelling to policy makers or the public. Defending a project on the basis of a small improvement in travel time for a large number of trips may not sound particularly convincing. For example, framing the benefits in terms of a change in the effective size of labor and business markets may sound more compelling, even if travel time savings plays some role in shaping the process[20]. In practice, when a positive net present value investment has been identified[21], the project should be explained in whatever terms will maximize the likelihood of it being understood.

2.4.2 Direct User Benefits

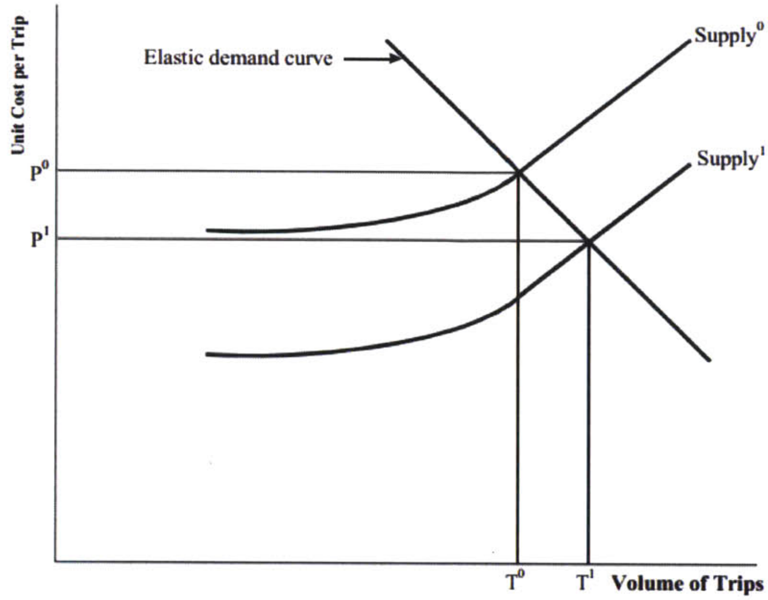
A traditional view is that investments in transportation will reduce the "cost" of travel by causing changes in:

- Travel time,
- Travel reliability,
- Out of pocket costs (e.g. fares, gas, vehicle depreciation),
- Discomfort or Anxiety.

Users who continue to make the same trip before and after the investment can capture the full benefit of the cost reduction. Users who change their travel habits in response to the investment, such as users who travel more or switch to a cheaper path, can benefit by some fraction of the cost reduction. A common, simplifying assumption is that, on average, the induced demand would receive 50% of the cost reduction in accordance with the so-called "rule of half" (DfT, 2014b). Figure 2-4 presents a simplified theoretical relationship between travel cost and demand.

[20] For example, while DfT's strategic case for the HS2 project does highlight the travel time savings benefits, the primary objective of the report is to argue that HS2 would help sustain growth and deliver economic benefits through improving "connectivity" (DfT 2013b)
[21] Including any opportunity cost from spending public money

Figure 2-4: Traditional Consumer Surplus Theory



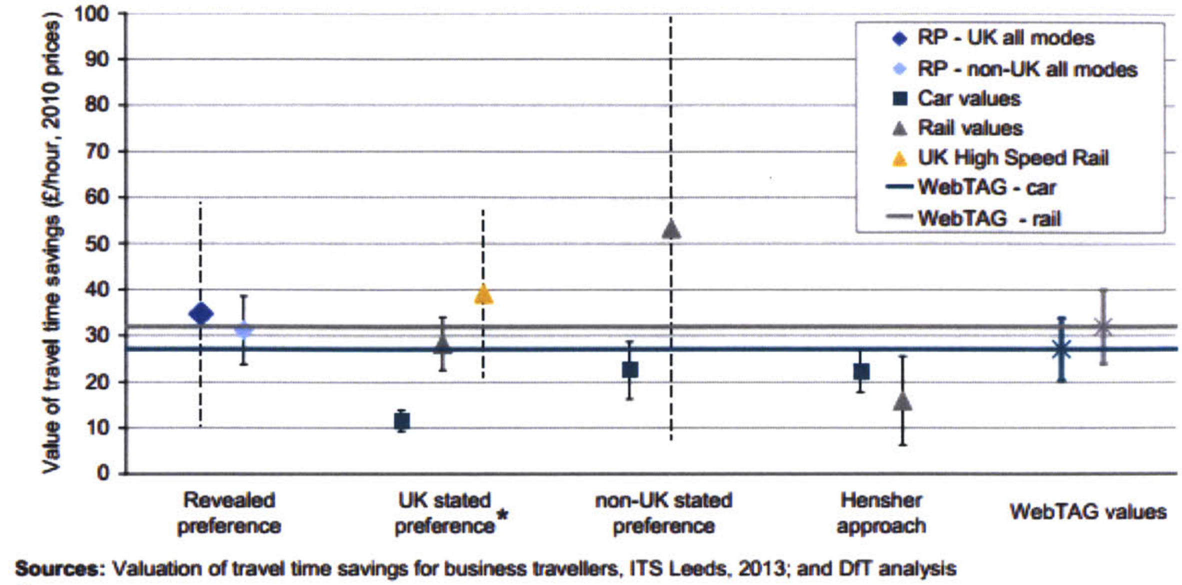
Source: (DfT 2014a)

The key challenge in estimating the change in the cost of travel is determining how much people "value" their time[22]. A "willingness" to pay for travel time savings can vary by user type and trip purpose, with business travel being recognized to have a higher value of time than other trip purposes. Business travel time savings could allow more work to be accomplished in a single day, or facilitate distant meetings. Figure 2-5 shows a range of values that have been estimated for business travel in the UK. An analogous method could be used to value the other temporal components of travel cost, such as reliability.

As discussed in section 2.1.3, users may place a different weight on their travel time in crowded conditions. It should be noted that because the assumed business value of time reflects a temporal constraint on productivity, it may not be appropriate to use weighted times in cost benefit analysis for these trips (DfT 2014c). However, improving service reliability and vehicle crowding levels would at least deliver a welfare benefit to commuters and non-business travelers, and potentially impact GDP by influencing willingness to travel or location decisions.

[22] A discussion on the valuation of travel time is not included in this research. David Hensher is one researcher who has written extensively on this topic (e.g. Hensher, 2001).

Figure 2-5: Dft Business Value of Time



Obtained From: (DfT 2014a)

2.4.3 Wider Economic Impacts

In the context of cost benefit analysis, wider economic impacts (WEIs) refer to externalities that are not captured in the travel time savings paradigm. In other words, WEIs are not synonymous with "land use" or "economic geography" impacts because, in theory, the travel time savings benefits can be absorbed into land markets and subsequent land use changes may have already been "counted" as a benefit.

However, this is certainly not imply that there is no value in exploring potential land use impacts from transportation investment. As discussed in section 2.4.1, a fixation on measuring travel time savings could distort the appraisal itself or introduce bad incentives for how planners and policy makers think about transportation.

This section enumerates several of the externalities that were shown to be significant omissions from cost benefit analysis.

Agglomeration

Agglomeration[23] benefits are a significant omission from the traditional appraisal process (Venables, 2007). As discussed in section 2.3.2, businesses will not consider the external effects of location decisions. For example, a business might move to a dense area and the surrounding firms could become more

[23] The theory of agglomeration is introduced in section 2.3.1.

productive from its presence. This is one way that transportation investment can directly create positive agglomeration externalities. A transportation investment could also make businesses "effectively" closer to each other, even if no business physically moves, thereby creating positive agglomeration externalities (DfT, 2014b).

In the most recent update to the Crossrail business case, analysts found that project might deliver agglomeration benefits between £27.1 billion and £28.6 billion over 60 years (TfL, 2011a). A light rail study in Tel Aviv found that project might deliver agglomeration benefits between 73 and 355 million dollars per year. A review of agglomeration benefits for other projects is included in Jenkins et al. (2011).

Tax Distortions

Venables (2007) developed a theoretical model to explain how household and business location decisions, which are influenced by transportation, can create tax externalities that benefit or hurt the treasury[24]. An important case is when a transportation investment causes businesses to move to a more productive area of a city, such as a business district. This benefit, referred to in UK appraisals as a "move to more productive jobs," can deliver a large tax receipt benefit to the treasury. The Crossrail business found that there could be a wide range of GDP estimates depending on the extent to which the jobs represent a redistribution or net increase in employment[25]. The NPV of welfare impacts of Crossrail from a "move to more productive jobs" was estimated to be between 2.3 and 28.1 billion pounds, while NPV of GDP impacts was estimated to be between £8.8 billion and £93.5 billion (TfL, 2011a).

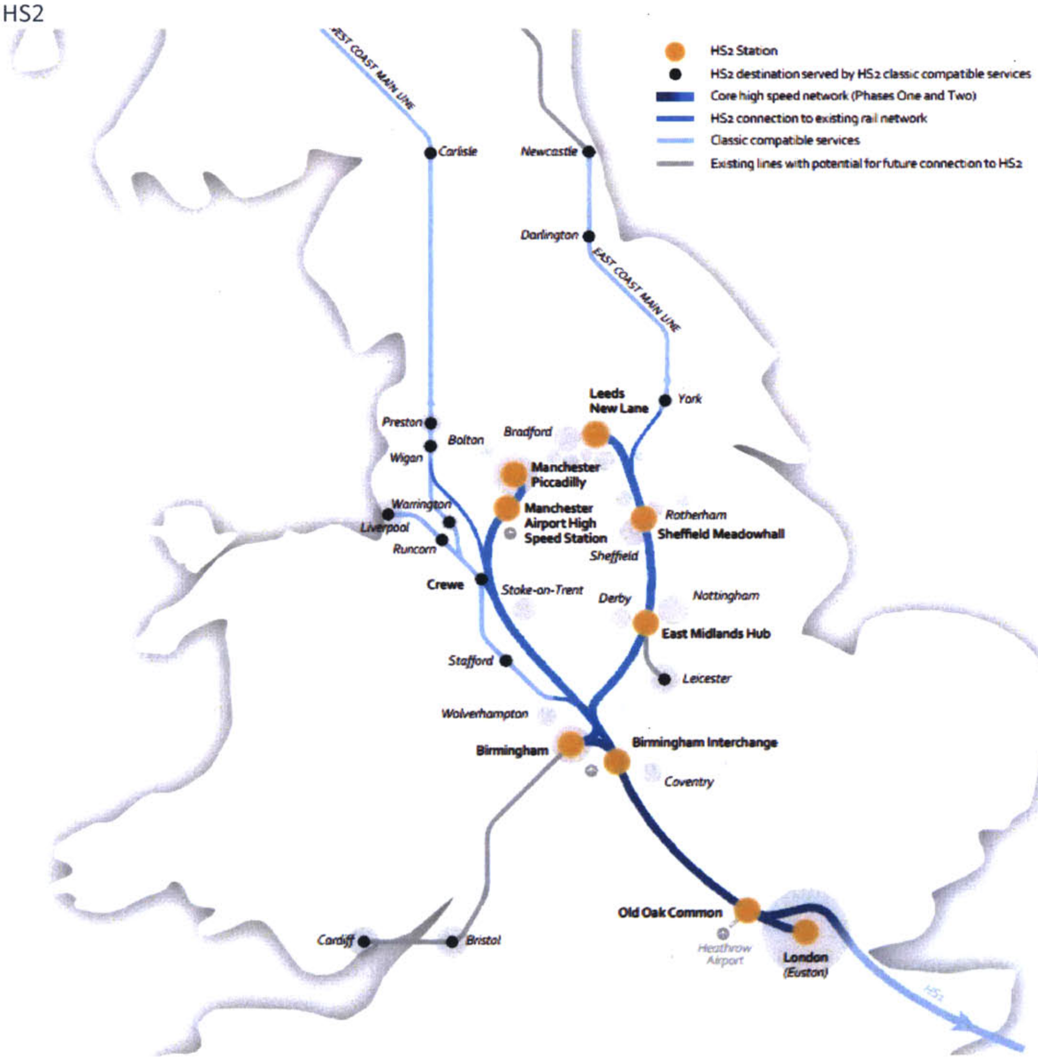
[24] For instance, a business might not move to a productive location because it does not want to face higher congestion levels or higher rents. However, when deciding whether to pursue an economic opportunity, businesses would consider the after-tax earnings impact, thereby resulting in less incentive to act than if they considered before-tax earnings. At the margin, some businesses might not act because of this tax wedge. In other words, some businesses would act if they could capture the after-tax benefit, but would not act if they can capture only the before-tax benefit. This represents a market failure. For example, even if a business is internally indifferent between moving and not moving to a productive center, society would still unequivocally benefit from the move because of the higher tax yield that the Treasury collects. To the extent that transportation investment can facilitate this type of move, then transportation investment creates a positive tax externality to the Treasury and to society.

[25] It should be noted that DfT requires cost benefit analyses to assume that any change in the location of jobs is a pure redistribution and does reflect a net gain. TfL examined the benefit from new job growth as a sensitivity test

3 HS2 AND LONDON PLANNING CONTEXT

The UK Department for Transport has published a strategic case for investing in a new high-speed rail (HSR), line, called HS2, that would run from London to Birmingham, fork at Birmingham, and extend to Manchester along one branch while continuing to Leeds along the other branch (2013b). DfT makes two key arguments for HS2. One argument is that cities in Northern and central Great Britain would benefit significantly from improved access to London and improved access to each other. The second argument is that inter-city rail services into London, particularly services on the West Coast Main Line (WCML), are reaching capacity and a new parallel rail line is needed to provide critical relief.

Figure 3-1: HS2



Sources: (Dft, 2013b; HS2 LtD)

The capacity relief is expected to benefit the region by reducing crowding levels on WCML services and providing flexibility to modify existing train schedules to enhance passenger service to smaller markets or to increase freight traffic. While the increased freight traffic could benefit the entire UK, the WCML capacity relief may be particularly important to London and the surrounding towns if it removes a constraint on growth in commuting.

Using standard appraisal methods and including wider economic impacts, the net present value (NPV) of the HS2 project is positive, with an expected benefit to cost ratio of 1.7 (see Dft, 2013a). Furthermore, the 2013 appraisal asserts that the risk of the project representing "poor" value for money, or a benefit to cost ratio of less than 1, is "negligible". However, the project has faced significant public scrutiny and criticism, drawing nearly 2000 petitions from various councils, businesses, and charities (Express & Star, 2014). The 2000 petitions exceed what was received for either Crossrail or HS1 and risk delaying the project.

3.1 HS2 Benefits and Challenges for London

London would have two HS2 stations: a station at Euston and a station at Old Oak Common (see Figure B-3). Euston station is the current WCML terminus in London, and would act as a central London node for the project. Old Oak Common is located outside of central London, but would have an immediate transfer point to Crossrail services (see Figure B-4) that head to central London, Stratford, and Canary Wharf in the eastbound direction, and head to Heathrow, and other, smaller market, in the westbound direction. The commercial viability of the land surrounding both stations is being closely evaluated.

As currently proposed, the HS2 project would deliver a mixture of benefits and disbenefits to London. Complementary investments, such as an extension of the West Coast Maine Line to Crossrail or new Overground stations(s) at Old Oak Common (see Figure B-6), could further strengthen benefits of the project or mitigate disbenefits.

The primary benefits to London from the current HS2 proposal include:

- New capacity on the WCML to enhance service to London's commuter markets. If HS2 is built, then there will be less demand for long-distance travel via the WCML, unlocking capacity that can be used to enhance connections to London's commuter markets.
- An increase in the maximum number of peak-hour trips from northern Great Britain to London that will relax a constraint on travel between these markets.

- Faster travel times that will increase inter-regional accessibility between London and parts of northern Great Britain. This reduction in travel time could make long distance business trips more palatable and facilitate interactions among employment centers across each region. Furthermore, thanks to improved accessibility, some businesses may be able to relocate to lower cost employment centers, potentially benefiting areas with high unemployment rates.[26]

Benefits to London from the HS2 project could be increased through a range of complementary investments. In particular, complementary investment could help London improve the development potential of the land near each stations. Adding new viable development sites is important for sustaining population and employment growth London, and HS2 presents an interesting opportunity to increase the supply of developable land (Figure B-5 shows current development proposals). At the same time, there are potential disbenefits caused by crowding at Euston which needs to be considered.

Major complementary investments to HS2 include:

- Extending the WCML to Crossrail. The specific path is still being considered, but the extension would likely occur near the Crossrail station at Old Oak Common (see Figure B-6). Besides crowding relief benefits (discussed blow), the WCML extension could also benefit sites in and around London by providing new accessibly. Communities in Hertfordshire would benefit from direct access to central London, potentially making them more attractive to developers. The extension could also lead to a further improvement in access to Old Oak Common by improving the connection to the north.

- Adding a new Overground station(s) at Old Oak Common (see Figure B-6). The new station(s) could benefit HS2 travelers by providing direct access to a number of sites outside of central London. The new station would also enhance the development potential of Old Oak Common. A number of Local councils are reviewing this opportunity, and see promising growth potential (see Figure B-7), including up to 19,000 new homes and 90,000 jobs over an area of 10 square kilometers (GLA, 2013). While the HS2 station and a new Crossrail station would be the primary catalysts for growth at Old Oak Common, a new Overground station could help improve connectivity to the site, particularly from population centers to the north and south.

[26] This effect could have important implications for the economic geography of the UK, which are not explicitly represented in standard cost benefit analysis.

The HS2 project would also present new crowding and capacity challenges for London. The project is expected to generate nearly 30,000 new AM period trips in the southeast of England (see Table 5-1), which could exacerbate conditions on Underground lines, including the Victoria and Northern, that are already expected to face significant crowding problems. New HS2 travelers would also exacerbate crowding within Euston Station.

The WCML extension is one idea to mitigate crowding challenges as the project could divert four or more passenger trains away from Euston (Beard, 2014). This diversion could thereby help relieve crowding on the Victoria Line and Northern Line and directly reduce levels within Euston Station. Furthermore, if the WCML extension is completed well in advance of HS2, then there would be significantly fewer trains and people going into Euston Station during a difficult construction period. This reduction in station crowding and train volume could help reduce potential interference with construction and limit the risk of schedule slippage. On the other hand, the WCML extension may present new crowding challenges for future Crossrail services in the long run, if other proposals to expand capacity, such as Crossrail II, are delayed.

4 TRANSPORTATION CAPACITY CHALLENGES AND ECONOMIC POTENTIAL

This chapter presents the author's hypotheses for how public transportation capacity constraints could impact economic potential. Three questions are examined:

1. How can a failure to address public transport capacity challenges degrade the economic potential of a location?
2. How could investment in public transport capacity unlock the economic potential of a location?
3. How can public transport capacity challenges influence the spatial distribution of disbenefits?

It is important to note that the ideas presented in this chapter are hypotheses and should not be interpreted as empirically-driven conclusions. However, some of the ideas presented in this chapter are tested or applied in scenarios in chapters 6-8.

4.1 Declining Accessibility

A location's economic potential will tend to decline as crowding in the transportation system degrades accessibility. Weisbrod and Reno (2009) indicate that insufficient public transportation capacity could present at least two challenges for employment centers. One challenge corresponds to the cost of accessing the site. As crowding levels grow worse, businesses may need to pay a "wage premium" to remain competitive in recruiting employees (Weisbrod and Reno, 2009). We can consider three cases:

1. For transit-captive commuters, crowding in public transportation systems has an inescapable, adverse effect. While this negative effect could be offset by a wage increase, if crowding levels grew too severe, then they might consider looking for a job elsewhere.
2. For commuters who can decide between public transportation and automobile use, the level of public transportation crowding could factor into which mode they will ultimately select. Selecting public transportation can reduce out-of-pocket automobile expenditure. In certain cases, the level of public transport crowding could affect as well automobile ownership rates, which can have a significant impact on real income.

3. For commuters who do not use public transportation and choose to drive to work, an increase in public transport crowding would tend to push choice riders back onto the roads, thereby increasing the cost of their commute.

The second way that capacity constrains in public transportation systems can limit economic development potential is by reducing agglomeration benefits, which are external to user benefits and motivations, and thus not measured in traditional user travel time savings based on cost benefit analsyis. As discussed in section 2.3.1, and reviewed in Duranton and Puga (2004), agglomeration benefits are composed of a number of business-to-business and labor-to-businesses effects. Given that public transportation crowding is more likely to be a factor during the peak period, the labor-to-business agglomeration benefits are directly threatened. In other words, the potential of a site to benefit from labor market agglomeration effects could be harmed from public transportation crowding conditions. There can also be direct business-to-business effects. While a good number of intra-city business trips may occur during the off-peak, inter-city business trips that arrive during the peak could be adversely affected. In the long-run, public transportation capacity challenges may also hurt business-to-business relationships by precluding further spatial concentration or clustering of jobs (see section 2.3).

The lost agglomeration and wage premium from caused by crowding challenges could be written as:

$$Agglomeration_{Lost} = Agglomeration_{Uncongested} - Agglomeration_{Congested}$$
$$Wage\ Premium = Wage_{Congested} - Wage_{Uncongested}$$

The key to understanding the agglomeration effect is to look at labor-to-business accessibility and possibly also business-to-business accessibility.[27] DfT's (2014a) current effective density measure of agglomeration is similar to a business-to-business accessibility measure, but something analogous could be developed for labor-to-business accessibility. The wage premium could be understood through the demand-weighted generalized cost to the site.

Making the simplifying assumptions that agglomeration is a function of accessibility and wage premium is a function of travel costs, the equations could be re-written as:

$$Agglomeration_{Lost} = f(Accessibility_{Uncongested} - Accessiblity_{Congested})$$
$$Wage\ Premium = f(Travel\ Cost_{Uncongested} - Travel\ Cost_{Congested})$$

[27] For example, using a weighted isochrone measure, a labor-to-business accessibility measure could be the number of people who can reach the site within 7 pounds of commuter time. The business-to-business accessibility measure could be the number of businesses that reach the site within 20 pounds of business time.

To understand how the site's economic potential is influenced by public transport capacity constraints, transit demand could be systematically varied along two, or more, dimensions. One dimension would be the total demand to the site. This would reflect how the site responds to its *own* growth. The second dimension would be the total demand in the system. This would reflect how the site responds to *external* growth. The rate of change in accessibility and travel cost would give an indication of the rate of change in agglomeration and wage premium. This information could potentially be used for several purposes:

- Measure how resilient a site is to further growth. At *some* point, the wage premium or lost agglomeration benefit would become large enough to deter or stop investment. This critical point would represent a type of nodal capacity constraint. The Crossrail business case may have implicitly assumed that this effect happens (see Dft, 2011a; Buchanan, 2007).
- Measure how *fast* the loss in agglomeration could occur and how *fast* the wage premium could rise. This would help identify the sites whose long-term potential is most threatened by a lack of available public transportation capacity.
- Measure where negative externalities from internal growth at the site occur. In other words, see what locations suffer from crowding as more trips are attracted to that site. This may be one way to assess how sites externalize or internalize the crowding they produce. The answer to this question could have potential implications for setting development impact fees.

Measuring these changes could be a slow process, requiring many demand scenarios. However, if the results are not biased by using a simple, frequency-based method (see section 2.1), then this assignment approach could be used to systematically test different levels of demand going to and around the site.

4.2 Unlocking Sites

Developers and businesses may simply overlook sites that do not have enough transportation capacity. As indicated in Table 2-2 and Table 2-3, there are a number of factors besides the availability of infrastructure that influence developer and business location decisions, and we need to recognize that transportation planners can play a critical role in shaping where growth occurs. For example, in the Canary Wharf case, TfL (2011b) believes that the recent growth in public transport demand driven by substantial employment growth (see Table 5-2) could not have been sustained without the Jubilee Line Extension.

While it might not be possible to reliably predict where the next Canary Wharf will happen, transportation planners could benefit from a clear understanding of the land supply in the region that can support dense development (as well as having knowledge of how much land can support medium or low density growth). Although the supply of this capacity is rival,[28] providing a wider array of potential sites in city might increase the probability that a developer finds at least one that is suitable based on their internal requirements and strategies. This could be particularly important if a foreign investor is evaluating a major move to the city. The traditional appraisal methods assume no increase in foreign investment from public transport projects. For example, in the Crossrail business case, when the jobs relocating to central London and Isle of Dogs were considered to be a net increase, as could be the case for new foreign investment, and not a redistribution of jobs, the net present value of the GDP benefits increase by over 50 billion pounds (TfL, 2011a).

4.3 Distribution of Disbenefits

As new growth exacerbates bottlenecks in large public transportation systems, the origin-destination pairs that suffer may not be the same ones who are generating the new growth. Furthermore, disbenefits could apply to sites that far away from the actual bottleneck. The potential for certain ODs to externalize their crowding benefits and the potential for other ODs to absorb these disbenefits may warrant further attention in transportation planning.

The strategic use of congestion pricing or development impacts might be justified if the externalization of crowding disbenefits was found to be large. In London's network, many ODs have more than one reasonable, distinct path. Also, creative adaptations to London's bus network could increase the number of such ODs. If these ODs can be identified, then they might become good candidates for applying a variable fare given that passengers can select a different path without suffering a major change in journey time. Of course, this might present technical challenges, given that a method to identify origin, destination, and route choice would be needed, or there could be customer relations problems. However, if successfully implemented, then capacity could be used much more efficiently.

OD pairs could be classified three ways:

- Whether they are a threat to exacerbate bottlenecks;
- Whether they are vulnerable to network crowing;

[28] If one developer seizes the public transport capacity, then it may not be available to another developer. For example, the Canary Wharf developer may have quickly seized much of the potential of the original Docklands Light Railway. On the other and, as noted in section 4.3, there may be cases where new growth can externalize crowding challenges. In these cases, the original developer would not be able to irreversibly seize capacity.

- Whether they can be efficiently managed through fare or other policy interventions.

OD pairs that send demand *through* bottlenecks are at least exacerbating capacity challenges. However, these ODs might also be vulnerable to crowding challenges. An example of an OD pair that exacerbates crowding, but it is not especially vulnerable to capacity challenges, at least in the AM period, is Waltham Stow to Victoria Station. Passengers can get a seat and ride to their destination without facing any major discomfort. As this OD pair grows, (almost) all the disbenefits would be passed to network users and land uses. However, in traditional transit assignment with link-based penalties, this OD would be assigned using a very large crowding penalty. Euston to Victoria Station would both exacerbate capacity challenges and be vulnerable to crowding challenges. In traditional transit assignment the discomfort penalty would be only medium given the short distance, even though this OD is vulnerable to crowding challenges.

OD pairs that require boarding into a bottleneck or require standing in crowded conditions for a significant amount of time are vulnerable to further network crowding. Although further growth in these OD pairs would exacerbate crowding problems, these ODs will tend to internalize all the disbenefits.

As for defined for this discussion, manageable OD pairs have two or more reasonable paths. For these ODs, variable public transport fares or other incentives could be strategically employed to influence path choice. A simple example of a manageable OD is Finsbury Park to King's Cross, where either the Victoria Line or Piccaddily Line could be used. For others ODs, the alternative path may need to include a bus component. As public budgets permit, there may be significant potential to creatively adapt the bus network to create more manageable OD pairs.

5 DATA, MODELS, AND METHODS

This chapter describes the data, models, and methods used to analyze public transport capacity constraints in the southeast of England. The chapter is divided into five sections:

1. The first section presents the study region and the zonal structures used in the analyses;
2. The second section presents the socioeconomic and travel demand data that are used in the analyses;
3. The third section presents the transportation infrastructure and supply data that were are in the analyses;
4. The fourth section presents the model developed for analysis of capacity constraints;
5. The fifth section presents the methods used to evaluate capacity constraints in the southeast of England.

5.1 Analysis Zones

Capacity constraints are analyzed at both the aggregate and disaggregate level in the southeast of England. This section describes how input and output data are spatially grouped. The first sub-section presents the aggregate zones and the second sub-section presents the disaggregate zones.

5.1.1 Aggregate Zones

The aggregate analysis is predominantly performed either at the English district level or at a further aggregation of English districts into custom, "super districts." There are also two custom super districts that are not aligned with the boundaries of English districts.

Inner London

Inner London, as defined in Figure 5-1, is one the super districts used in the analyses. Some of the English districts that compose Inner London are also used individually. The boundaries of the Inner London district was taken from a TfL GIS file. The Inner London district contains the majority of the jobs and (7AM-10AM) transit destinations in London (see Figure 5-7 and Figure 5-10).

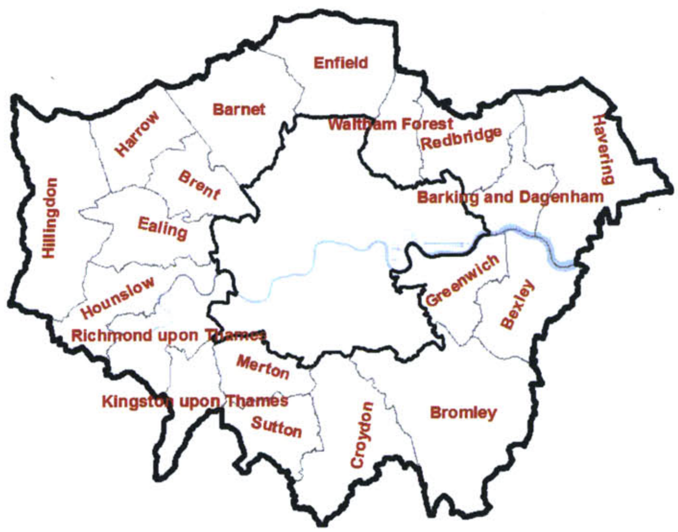
Figure 5-1: Inner London District

GIS Data Source: (ONS)

Outer London

Figure 5-2 presents the Outer London super district, which contains the remaining London boroughs. A number of these boroughs are used individually in analysis. More than half of London's population lives in Outer London, and a nearly half of AM transit trips originate there (see Figure 5-7 and Figure 5-9).

Figure 5-2: Outer London District



GIS Data Source: (ONS)

Commuter Ring

Figure 5-3 presents the Commuter Ring. There was no formal decision rule by which districts were included in the Commuter Ring. The goal was to create a modestly-sized perimeter around London that contains some of the districts that would be most impacted by HS2 or the WCML extension. The Commuter Ring contains a significant number of people and jobs, but contains proportionally less public transport origins and destinations than in London (see Figure 5-7, Figure 5-8, Figure 5-9, and Figure 5-10).

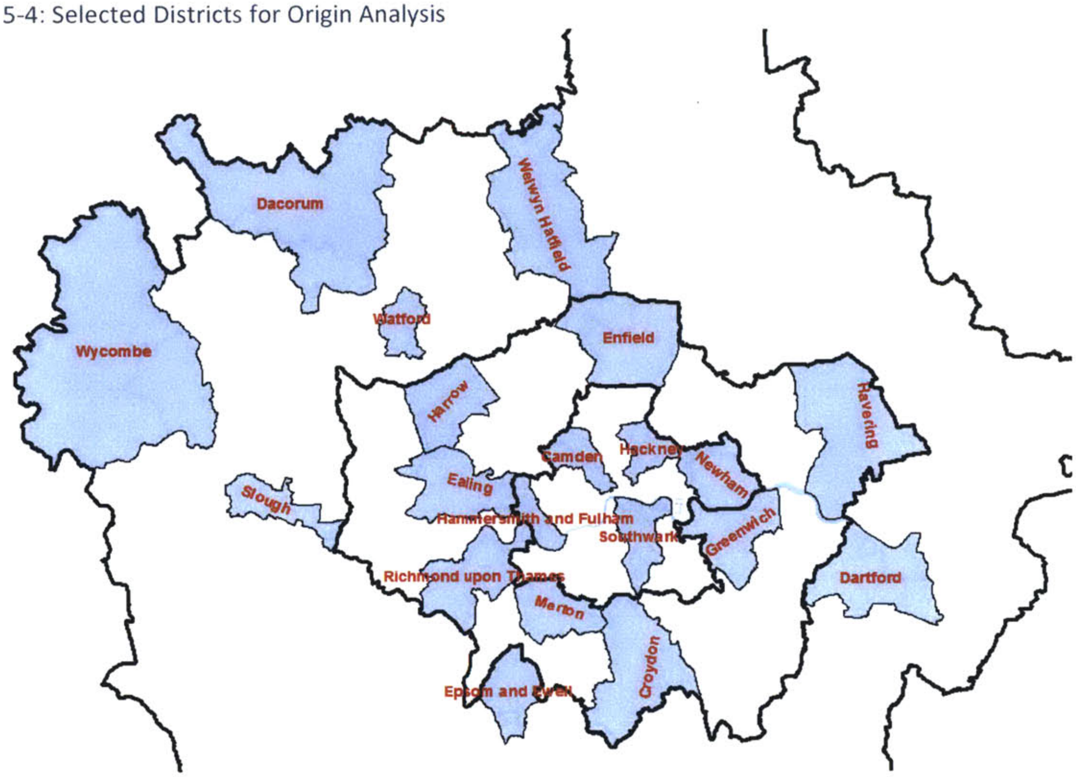
Figure 5-3: Commuter Ring

GIS Data Source: (ONS)

Selected Origin Districts

Altogether, the Inner London, Outer London, and Commuter Ring super districts include 65 English districts. In order to limit the number of rows in tables presented in this thesis, a subset of these districts was selected to be featured in certain analysis tables, particularly relating to capacity constraints on the trip origin end. Figure 5-4 shows which districts were selected for origin analysis. No hard rules were used in choosing these districts. The goal was to balance spatial representation, while highlighting land uses that may be impacted by HS2 or the WMCL extension.

Figure 5-4: Selected Districts for Origin Analysis

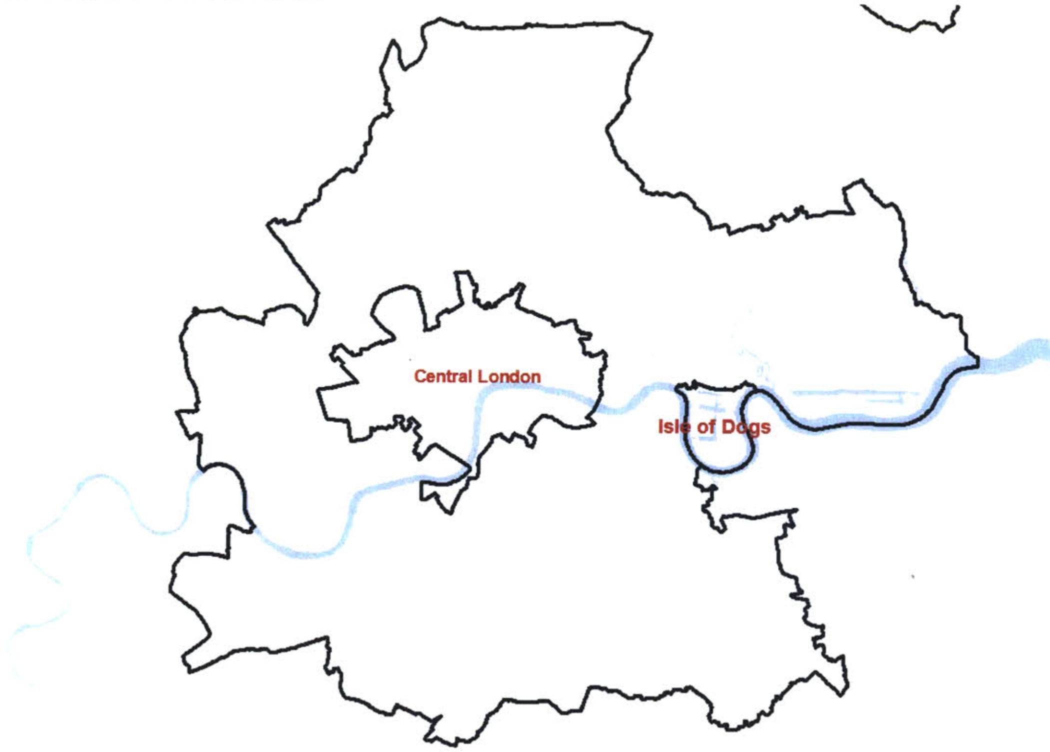


GIS Data Source: (ONS)

Special Destination Zones

Figure 5-5 presents two special zones that were created for destination analysis. The first special zone, Central London, which was based on a TFL GIS file, contains most of the highest density employment sites in Westminster and the City of London (see Figure 5-8). The second special zone, the Isle of Dogs, contains the Canary Wharf development site, which is another high density employment center in London.

Figure 5-5: Special Destination Zones

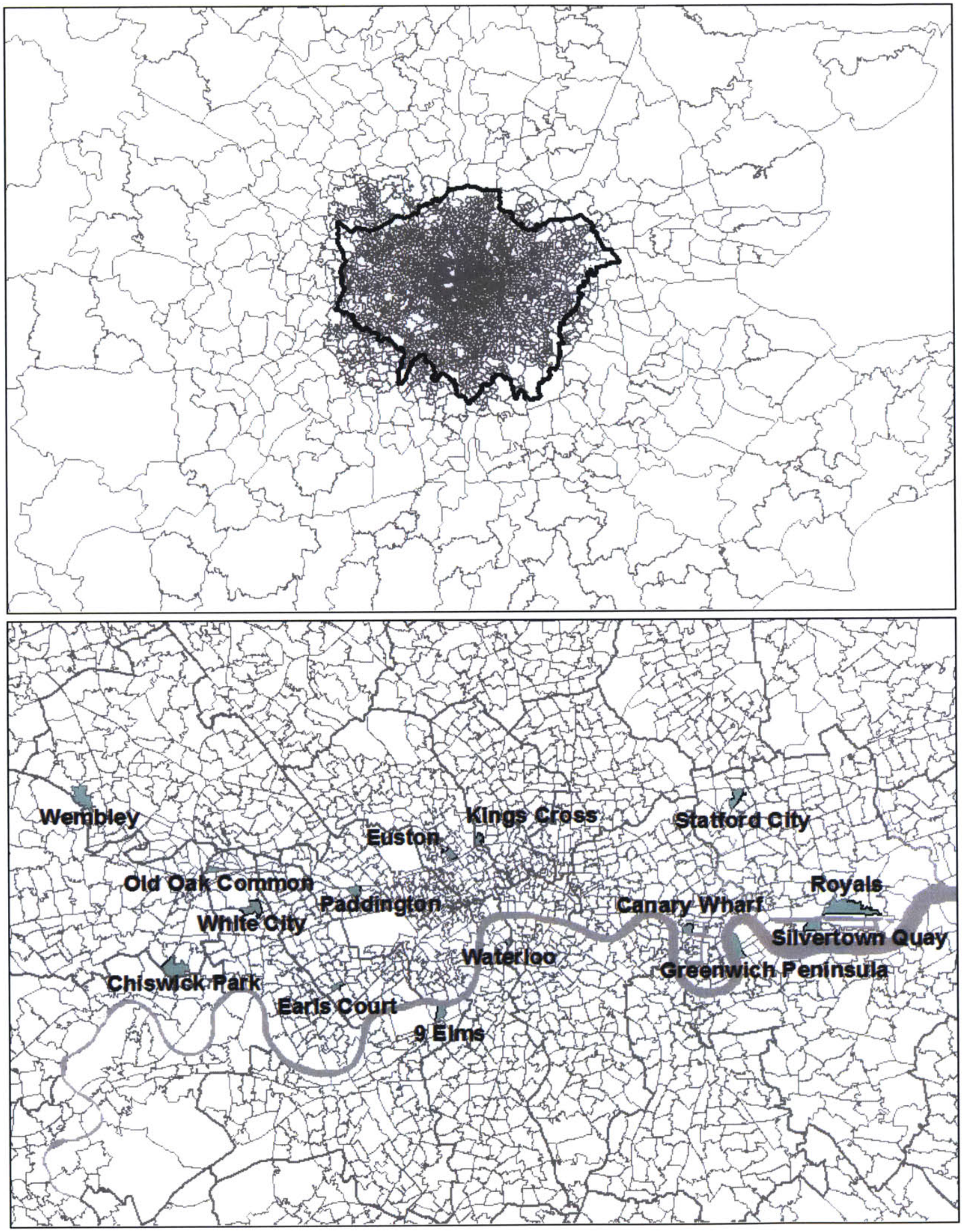


GIS Data Source: (TfL)

5.1.2 Disaggregate Zones

Disaggregate analysis in this thesis is done at the Traffic Analysis Zone (TAZ) level. The TAZ structure (see Figure 5-6) was developed by TfL and contains 4081 zones. A subset of the TAZs was chosen by the author (see Figure 5-6) to approximately represent the location of future development in London, as identified by Jones Lang LaSalle (see Figure B-5). The selected TAZs do not represent the actual shape or size of the development sites, but may reflect appropriate travel costs and levels of accessibility.

Figure 5-6: TAZ Structure and Development Sites



GIS Data Source: (TfL)

5.2 Socioeconomic and Travel Demand Data

This section reviews the socioeconomic and travel demand data used in analysis.

5.2.1 Census Population and Employment Data

Census resident and workplace population data were used for two purposes. The first purpose was to attain a better understanding of where the major trip producers (e.g. households) and trip attractors (e.g. businesses) are located in the southeast of England. The second purpose of the Census data was to represent the land use component of accessibility measures.

The resident and workplace population data were downloaded from the UK Office for National Statistics (ONS) via the NOMIS website for the years 2001 and 2011.[29] The resident population data were downloaded at the output area (OA), the middle layer of the super output area (MSOA), and at the district level. The 2011 workplace population data were downloaded at the OA and MSOA levels. However, the 2001 workplace data were not immediately available at a disaggregate level, and were only examined at the district level. The appropriate GIS layers were also downloaded from the ONS website.

Population and employment[30] data were studied at the disaggregate level through GIS. Figure 5-7 presents a dot density map of the 2011 population data at the MSOA level. While Inner London contains some higher density areas, the distribution of population within London is relatively diffuse. Outside of London, there are some higher density population centers, but the distribution is significantly sparser.

Much of the employment data, as shown in Figure 5-8, is concentrated in Central London. The other high density center exists in the Isle of Dogs, which contains Canary Wharf development site. There are also employment centers outside of Greater London that mirror the location of residential centers.

The summary table presented at the end of this section (see Table 5-1) includes a comparison of 2001 and 2011 population and employment data at an aggregate level. This table shows that Westminster and Tower Hamlets, which contains Canary Wharf, experienced the largest job growth in this decade.

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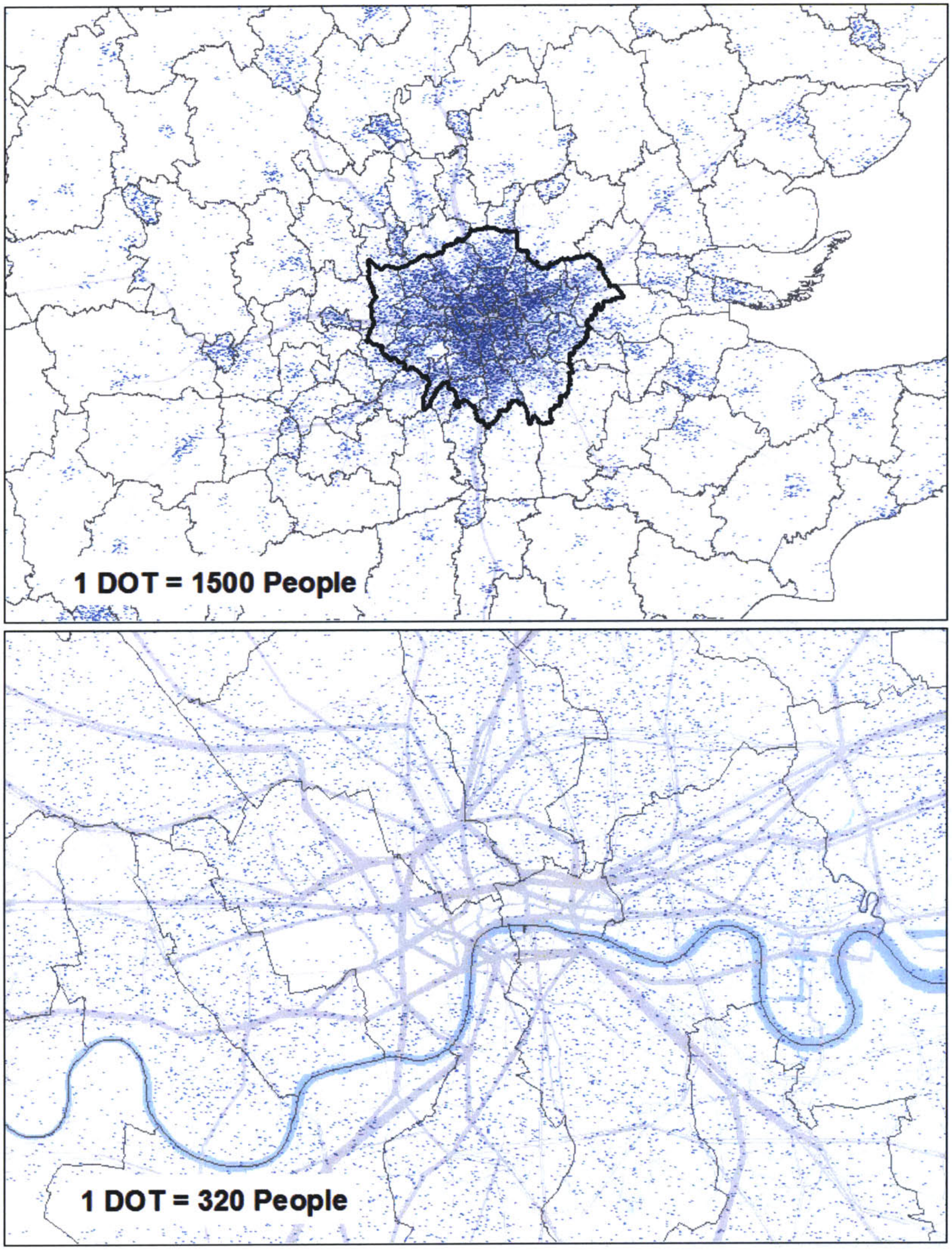
[29] These data contain public sector information licensed under the Open Government Licence v2.0. This license applies to all other ONS references in this research.

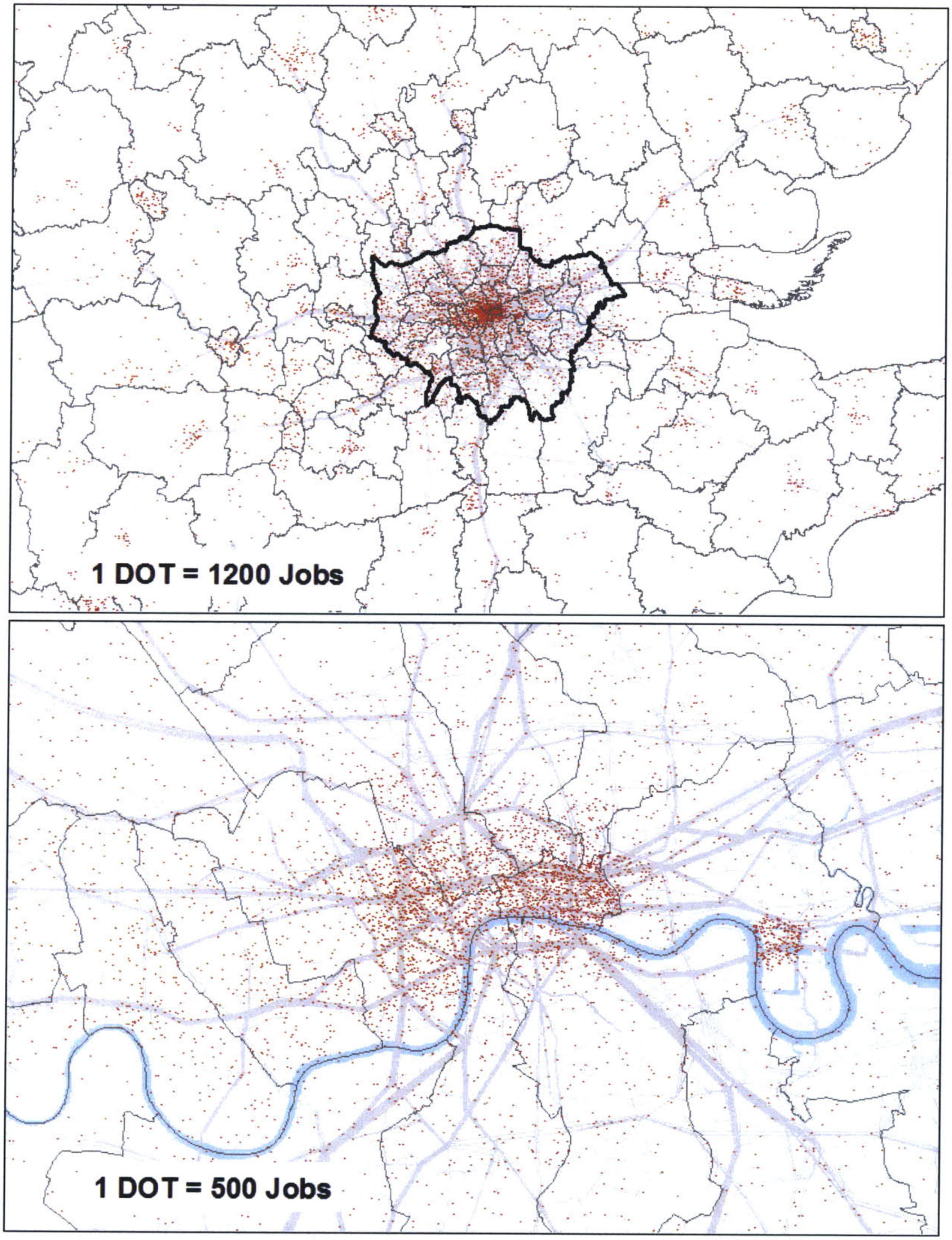
[30] For simplicity, the ONS resident population data is hereafter referred to as 'population' data and the ONS workplace population data is referred to as 'employment' or 'job' data.

Figure 5-7: 2011 Resident Population at MSOA level



Data Source: (ONS)

Figure 5-8: 2011 Workplace Population at MSOA level



Data Source: (ONS)

5.2.2 Public Transport Demand Data

The impact of public transport capacity constraints cannot be understood without public transport demand data. Total public transport demand and the spatial distribution of public transport demand are needed to carefully determine whether public transport supply is adequate. Aggregate methods that simply compare total public transport demand against total public transport supply cannot capture the spatial element of demand and supply.

Three public transport demand matrices were provided by TfL. These matrices list the number of AM trips (7AM-10AM) between origins and destinations in Great Britain. The three scenarios provided were:

- Base: a 2007 base year scenario.
- No Build: A 2041 scenario that assumes HS2 is not built
- HS2: A 2041 that assumes HS2 is built

In addition to being used in transit assignment to study capacity constraint, these demand matrices were used to infer which land uses in the southeast of England have a high transit share, and which land uses are expected to see the most public transport growth. Based on the assignment results, these matrices can also be used to determine which land uses are most associated with crowding challenges and infer where growth is exacerbating crowding problems and where growth is actually threatened by crowding problems.

This thesis does not provide a detailed review of how these demand matrices were developed since the matrices were developed by TfL and shared with the author.[31] In short, most of the public transportation demand in the southeast of England is an output from TfL's multi-modal model, London Transportation Studies (LTS). Public transport demand for other parts of Great Britain is obtained from various external sources. The public transport demand matrices are then used as in input to the strategic public transportation assignment model named Railplan (see section 5.3).

These matrices are a critical input into the transit assignment model used in this thesis, and any significant flaw could introduce major biases in the output. Inappropriate assignment results, such as volume to capacity ratios in excess of one, can be used to identify potential problems with the matrices. However,

[31] Detailed questions about the trip matrices should be directed to TfL

addressing this type of problem might require editing or re-estimating the matrix. This type effort was beyond the scope of the thesis.

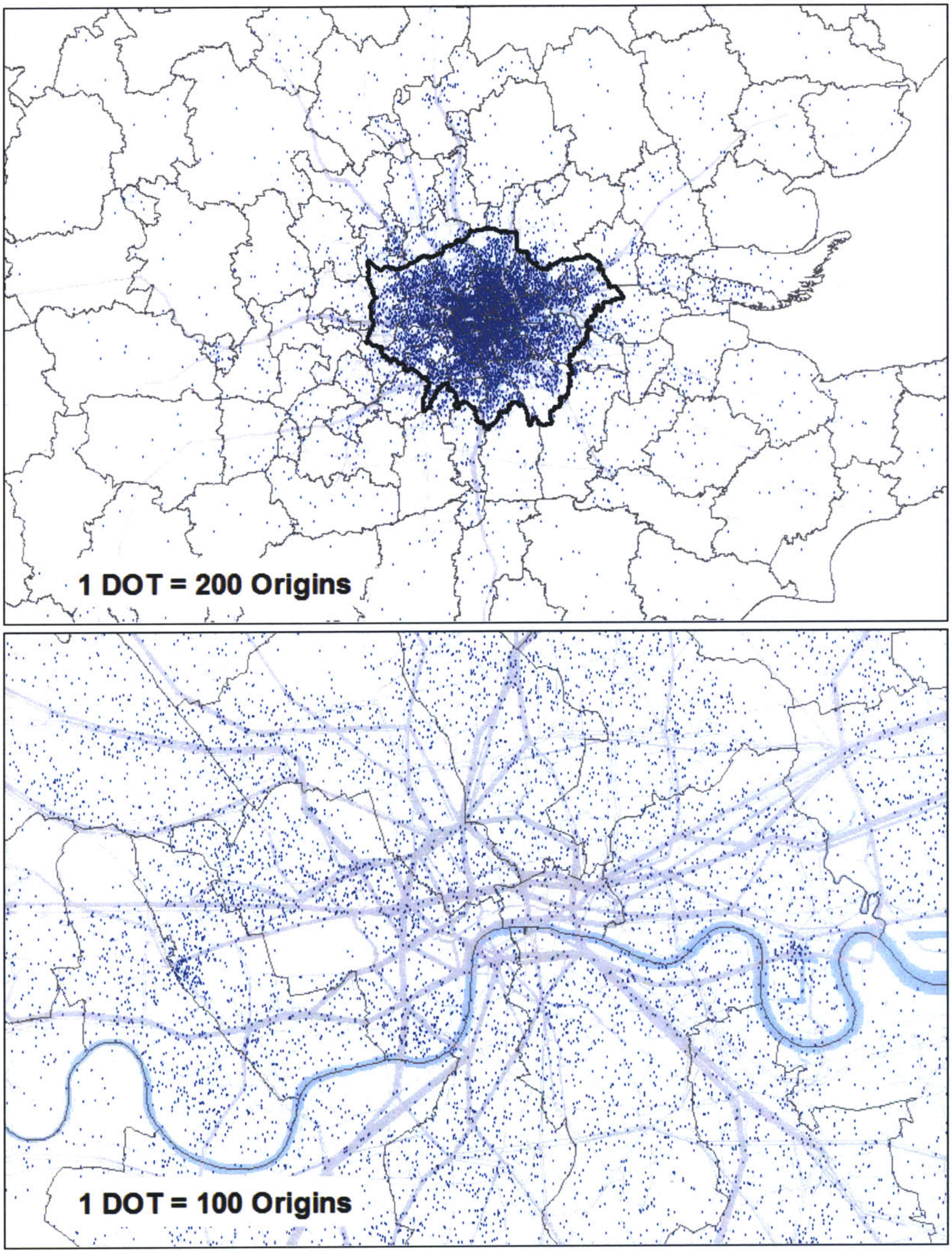
However, as shown in section 6.1, there are links in the network where demand is assigned well beyond capacity. This result could reflect errors in the assumed volume or spatial distribution of demand, as well as errors in representing transportation supply. To the extent that the spatial distribution of assumed demand could be flawed, then the model outputs in this research would be biased.

Zonal Trip Ends

Figure 5-9 shows the total trip origins for each TAZ in the No Build scenario. While the distribution of origins resembles the distribution of population (see Figure 5-7), the ratio of people to origins is highest in areas with poor public transport service (see Figure 5-15). In particular, population centers outside of London make relatively fewer public transport trips than population centers inside London. The same type of relationship exists for public transport destinations, where the distribution of public transport destinations resembles the distribution of jobs, but with relatively fewer trip ends in land uses with poor public transport service.

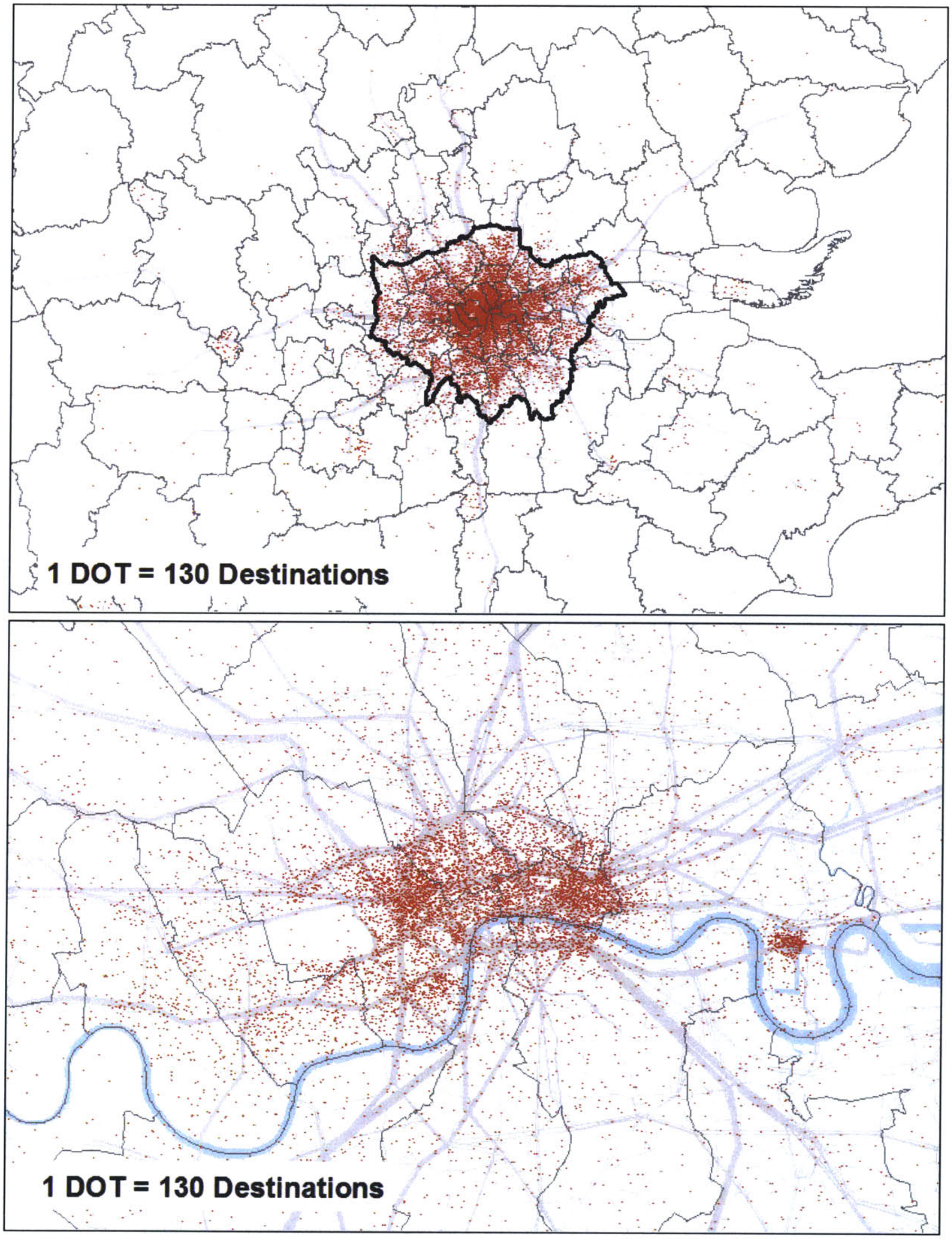
Substantial public transportation growth from 2011 to 2041 is predicted for the southeast of England, with over 650,000 more trip destinations predicted to occur in London. Figure 5-11 presents a dot density map of the growth in trip origins. While much of the southeast of England is expected to see substantial growth in trip origins, sections of east London are predicted to see the heaviest growth. Figure 5-12 shows the growth in trip destinations. The existing major, employment centers in Westminster, City of London, and Canary Wharf, are expected to see further, heavy growth in public transport destinations.

Figure 5-9: 2011 AM Trip Origins



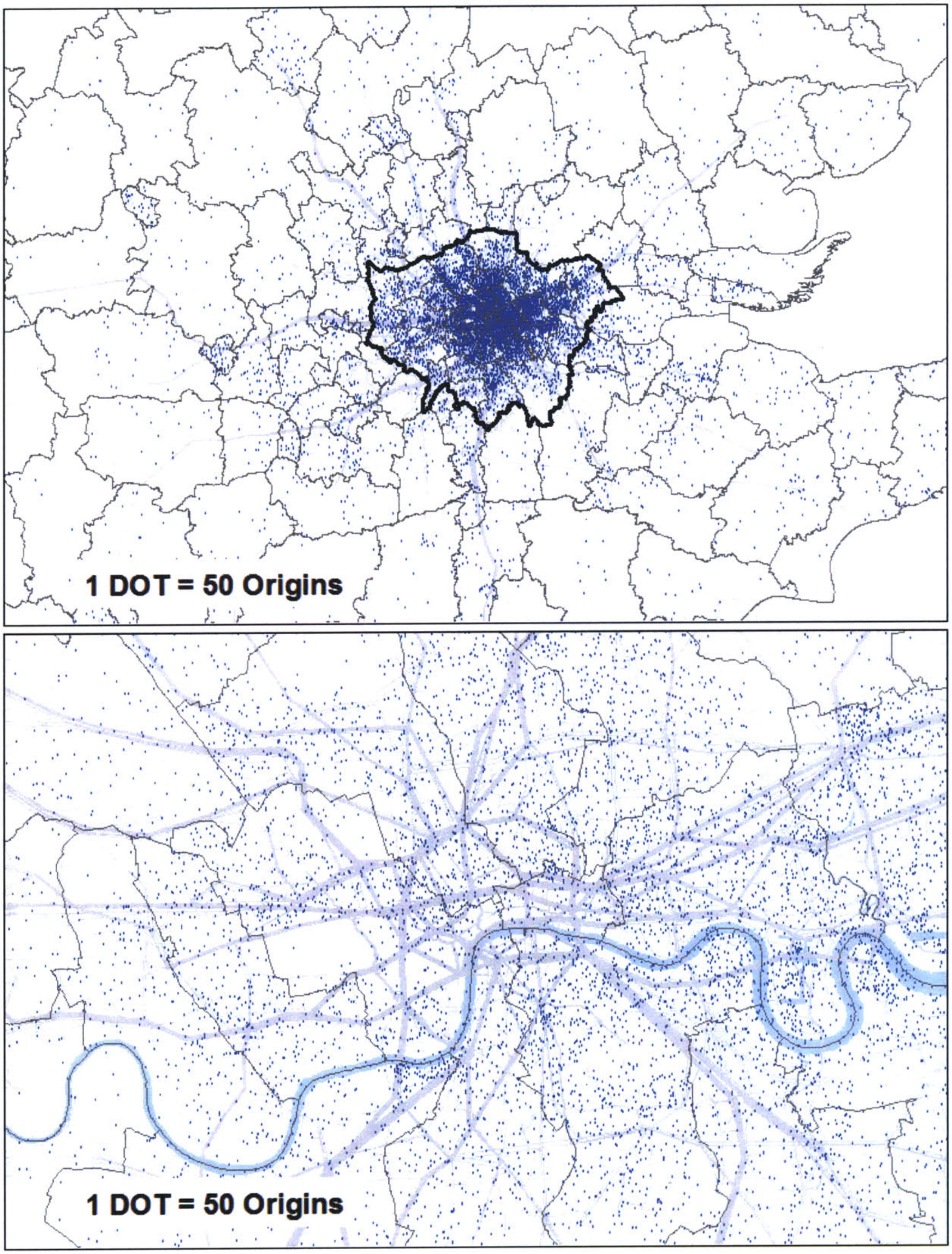
Data Source: (TfL)

Figure 5-10: 2011 AM Trip Destinations



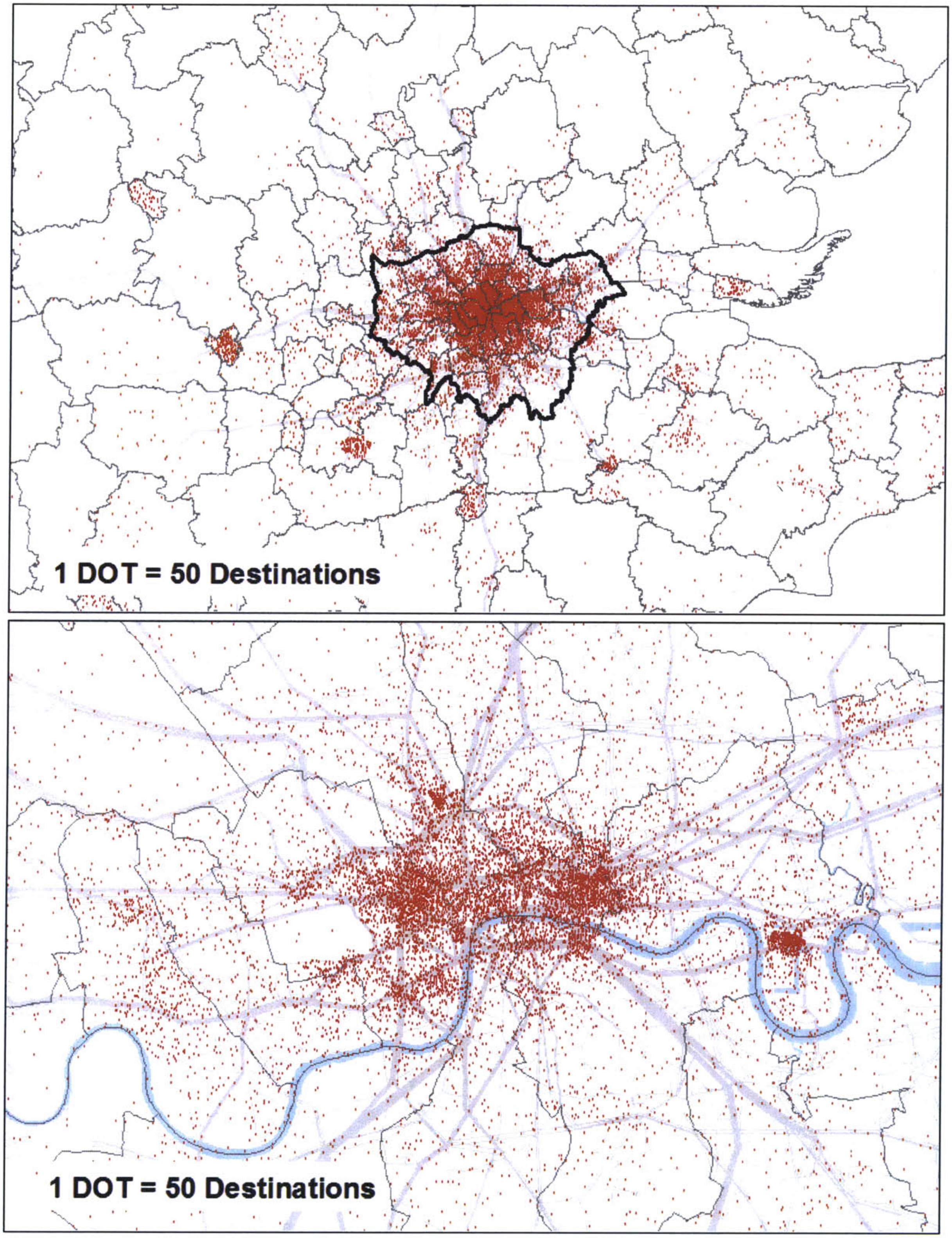
Data Source: (TfL)

Figure 5-11: AM Trip Origin Growth from 2011 to 2041



Data Source: (TfL)

Figure 5-12: AM Trip Destination Growth from 2011 to 2041

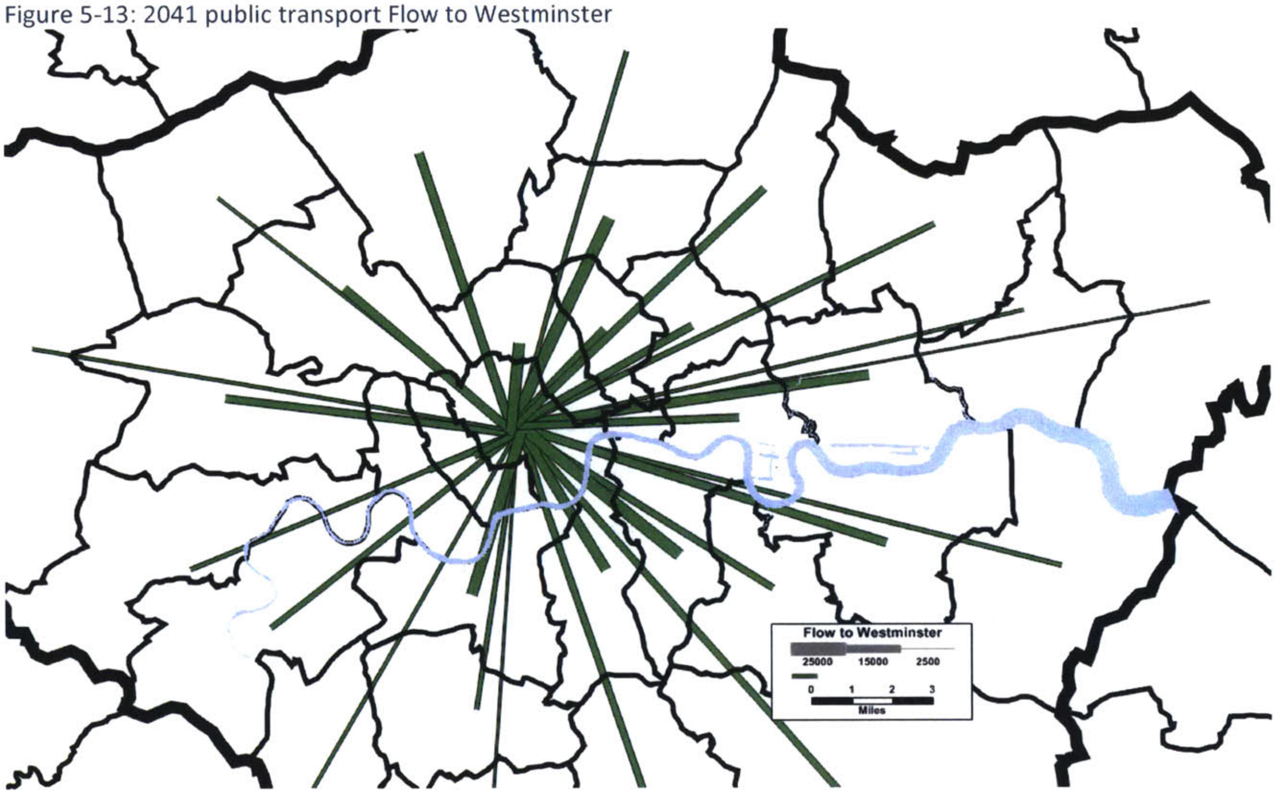


Data Source: (TfL)

Demand Matrix Data

Desire lines, which show the flow between OD pairs, are one technique for visualizing a travel matrix. Figure 5-13 shows the No Build flow from each district in London to Westminster. Westminster was selected as a representative case study because it contains a major employment center in central London, and can approximately illustrate the relative distribution of demand coming from each district to central London for work. The map shows that a relatively high number of trips are coming from the north and east of Westminster.

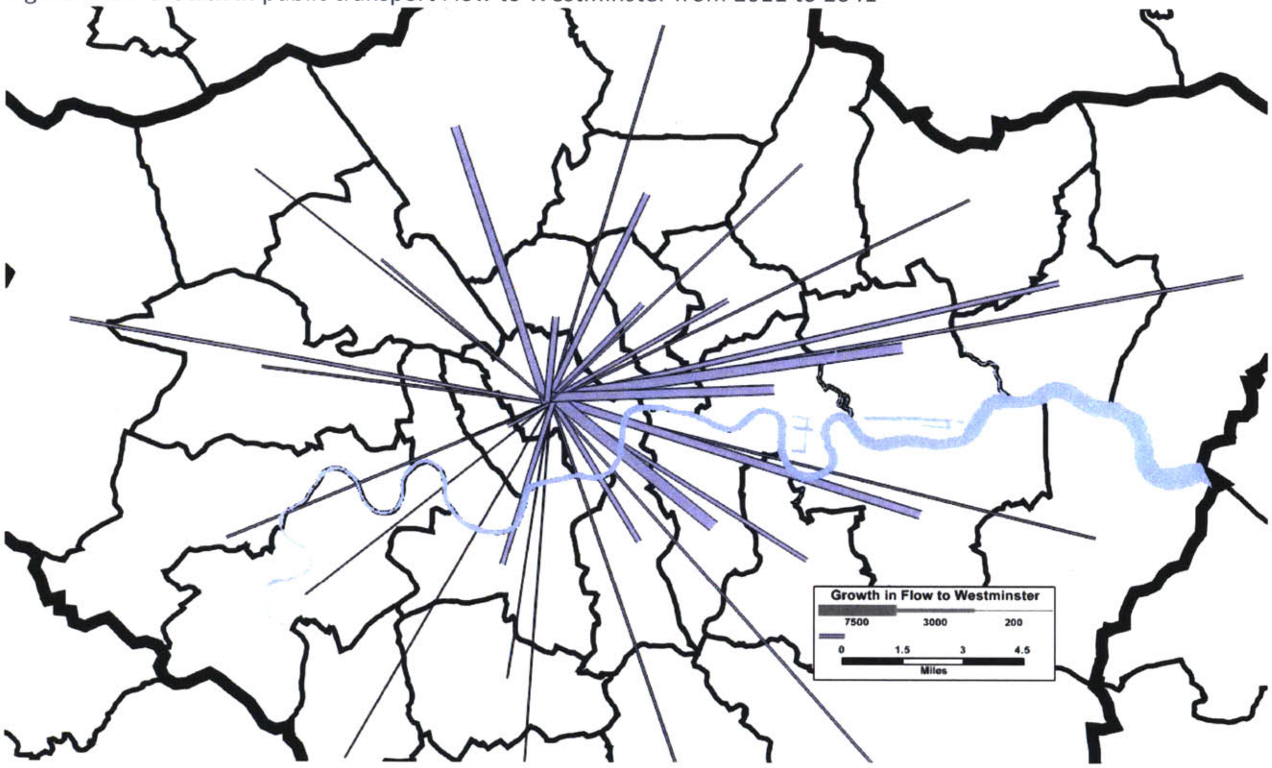
Figure 5-13: 2041 public transport Flow to Westminster



Data Source: (TfL)

Figure 5-14 shows the 2011 to 2041 growth in public transport flow to Westminster. This map indicates that much of the growth will come from the east and southeast of Westminster.

Figure 5-14: Growth in public transport Flow to Westminster from 2011 to 2041



Data Source: (TfL)

A second technique for exploring a large matrix is to aggregate the matrix into a simpler structure. Table 5-1 presents an aggregation of the three public transport demand matrices, and show which aggregate, zonal pairs are expected to grow the most. The demand matrices show that public transport flows are expected to grow by a substantial amount in the southeast of England, with demand to and from historically important centers, such as central London, growing by over 35%. In relative terms, the Isle of Dogs is expected to see a high degree of growth, with over 70% more trips destinations coming from London.

The number of AM outbound trips originating in London is expected to increase over 100% increase. This is an interesting prediction because outbound travel is less constrained and may appear increasingly attractive as crowding grows worse.

HS2 is expected to generate nearly 30,000 new AM trips in the southeast of England. A substantial fraction of these trips are going to central London or the City of London, indicating that these are predominantly work trips.

Table 5-1: Aggregation of Demand Matrices

Scenario		City	Central	Isle	Inner	London	HS2	Other
Base Scenario	City of London	1,015	2,567	40	5,165	6,232	0	1,063
	All Central	9,631	38,260	29,293	70,115	80,699	0	6,800
	Isle of Dogs	500	1,953	214	8,369	13,785	0	746
	All Inner	80,817	348,750	19,086	694,226	809,663	0	36,405
	All London	148,223	649,459	39,137	1,152,355	1,555,609	0	72,392
	HS2	0	0	0	0	0	-	0
	Other	64,786	230,747	17,408	315,627	338,954	0	115,552
Absolute Growth	City of London	381	1,730	96	3,570	4,462	0	1,493
	All Central	3,444	18,565	14,835	34,785	41,115	0	10,196
	Isle of Dogs	1,307	5,005	1,586	10,338	11,533	0	672
	All Inner	29,851	131,648	16,111	291,097	338,552	0	43,612
	All London	51,957	219,621	28,471	447,583	580,771	0	71,281
	HS2	0	0	0	0	0	-	0
	Other	24,585	112,872	10,459	169,252	184,227	0	132,567
Relative Growth	City of London	37.6%	67.4%	237.9%	69.1%	71.6%	0.0%	140.4%
	All Central	35.8%	48.5%	50.6%	49.6%	50.9%	0.0%	149.9%
	Isle of Dogs	261.4%	256.2%	740.3%	123.5%	83.7%	0.0%	90.1%
	All Inner	36.9%	37.7%	84.4%	41.9%	41.8%	0.0%	119.8%
	All London	35.1%	33.8%	72.7%	38.8%	37.3%	0.0%	98.5%
	HS2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Other	37.9%	48.9%	60.1%	53.6%	54.4%	0.0%	114.7%
No Build Scenario	City of London	1,397	4,297	137	8,735	10,694	0	2,557
	All Central	13,076	56,824	44,128	104,900	121,814	0	16,995
	Isle of Dogs	1,807	6,958	1,800	18,707	25,318	0	1,417
	All Inner	110,668	480,398	35,197	985,323	1,148,215	0	80,017
	All London	200,180	869,080	67,608	1,599,938	2,136,380	0	143,673
	HS2	0	0	0	0	0	-	0
	Other	89,371	343,619	27,867	484,879	523,181	0	248,119
HS2 Growth	City of London	0	0	0	1	3	373	-212
	All Central	0	0	0	6	21	2,477	-1,593
	Isle of Dogs	0	0	0	0	2	131	-80
	All Inner	0	0	0	22	91	12,721	-8,419
	All London	0	1	1	68	227	21,475	-14,339
	HS2	4,875	19,597	954	27,262	29,352	-	4,791
	Other	-1,974	-7,595	-202	-10,850	-11,983	4,749	-5,073

Data Source: (TfL)

5.2.3 Summary

Table 6-1 presents a summary table of the socioeconomic and public transport demand data contained in section 5.2.2. The table also includes a comparison of 2001 and 2011 Census population and employment data. Tower Hamlets, which benefited from the JLE, is shown to have strong population and job growth during the decade both in relative and absolute terms. Southwark, which also benefited from the JLE, had substantial population and job growth, in relative terms.

Table 5-2: Summary of Socioeconomic and public transport Demand Data

	Pop (1000s)			Jobs (1000s)			Origins (1000s)			Dests (1000s)		
	2001	2011	Δ	2001	2011	Δ	2011	2041	Δ	2011	2041	Δ
Central London	171	201	30	-	1,353	-	87	139	51	880	1,213	332
Isle of Dogs	23	38	15	-	119	-	15	27	12	57	95	39
All Inner London	2,766	3,232	466	2,169	2,658	489	832	1,201	370	1,411	1,989	578
All London	7,172	8,174	1,002	3,806	4,500	694	1,613	2,253	640	1,838	2,564	726
Commuter Ring	3,324	3,571	247	1,541	1,678	137	820	1,147	327	409	606	197
City of London	7	7	0	312	357	45	7	13	6	213	290	77
Tower Hamlets	196	254	58	157	235	78	56	103	47	121	200	79
Camden	198	220	22	228	272	44	60	85	25	164	232	68
Croydon	331	363	32	128	120	-8	62	79	17	38	46	8
Ealing	301	338	37	110	132	22	61	75	14	32	44	12
Enfield	274	312	38	90	105	15	44	55	11	25	31	6
Greenwich	214	255	41	65	86	21	46	90	44	26	41	15
Hackney	203	246	43	74	104	30	55	81	26	39	57	18
Hammersmith	165	182	17	100	125	25	47	58	11	49	77	28
Harrow	207	239	32	68	74	6	33	38	5	17	22	5
Havering	224	237	13	76	85	9	33	49	16	19	26	7
Merton	188	200	12	66	75	9	40	45	5	19	24	5
Newham	244	308	64	67	104	37	58	109	51	38	63	25
Richmond	172	187	15	68	78	10	31	37	6	17	21	4
Southwark	245	288	43	142	183	41	71	119	48	105	159	54
Westminster	181	219	38	510	580	70	86	113	27	394	537	143
Lambeth	266	303	37	113	138	25	76	101	25	63	87	24
Islington	176	206	30	138	167	29	52	76	24	90	128	38
Wandsworth	260	307	47	98	118	20	81	107	26	45	61	16
Kensington	159	159	0	102	117	15	51	67	16	87	109	22
Dacorum	138	145	7	69	66	-3	5	8	3	1	3	2
Dartford	86	97	11	47	55	8	7	13	6	4	7	3
Epsom and Ewell	67	75	8	27	30	3	8	10	2	4	5	1
Slough	119	140	21	72	75	3	4	7	3	2	4	2
Watford	80	90	10	49	51	2	7	10	3	6	8	2
Welwyn Hatfield	98	111	13	55	68	13	6	9	3	2	3	1
Wycombe	162	172	10	79	81	2	4	6	2	1	2	1

Data Sources: (ONS; TfL)

5.3 Public Transport Supply Data

Most of the public transport service assumptions used in this study were borrowed from Railplan, TfL's public transport assignment model[32]. Railplan public transport assumptions were used, in whole or in part, to define:

- The public transport network structure,
- Vehicle frequencies,
- Vehicle speeds,
- Vehicle capacities,
- The walk network,
- Walk times, including within stations.

A few significant edits were made to the default Railplan public transport assumptions. One edit involved adjusting the train capacities. According to the Railplan documentation (2006), a train can physically accommodate up to 7 people per square meter. However, this is the maximum, standing capacity of one vehicle and not necessarily a level of crowding that would be tolerated on a regular basis. For example, it might be possible to convince a group of people to load a train up to 7 people per square meter for one trip, but the same group might be unwillingly to make this trip every day. Furthermore, in a frequency-based assignment model, the assumed maximum capacity must be sustainable in every train car over the course of the entire period. Attempting to load every car to this level of crowding over a sustained period of time may not be possible if there is any deviation from perfect systems operations. A vehicle standing capacity of 4 people per square meter was assumed to be sustainable over the course of the assignment period. This level of crowding is in line with planning guidelines and what was suggested in Figure 1-1 as the "maximal" level of crowding.

According to the 2006 documentation, bus capacity constraint is not represented in Railplan. One reason for using infinite bus capacities may be to facilitate model convergence. A second reason for using infinite bus capacities is that bus frequencies can be increased, to some extent, in response to observed crowding. However, in reality, there is a limit to how many buses could be added to any corridor, and adding more buses might exacerbate roadway congestion problems and decrease the benefit to users. Nevertheless, it

[32] A comprehensive review of Railplan was beyond the scope of this project. Any questions about Railplan should be directed to TfL.

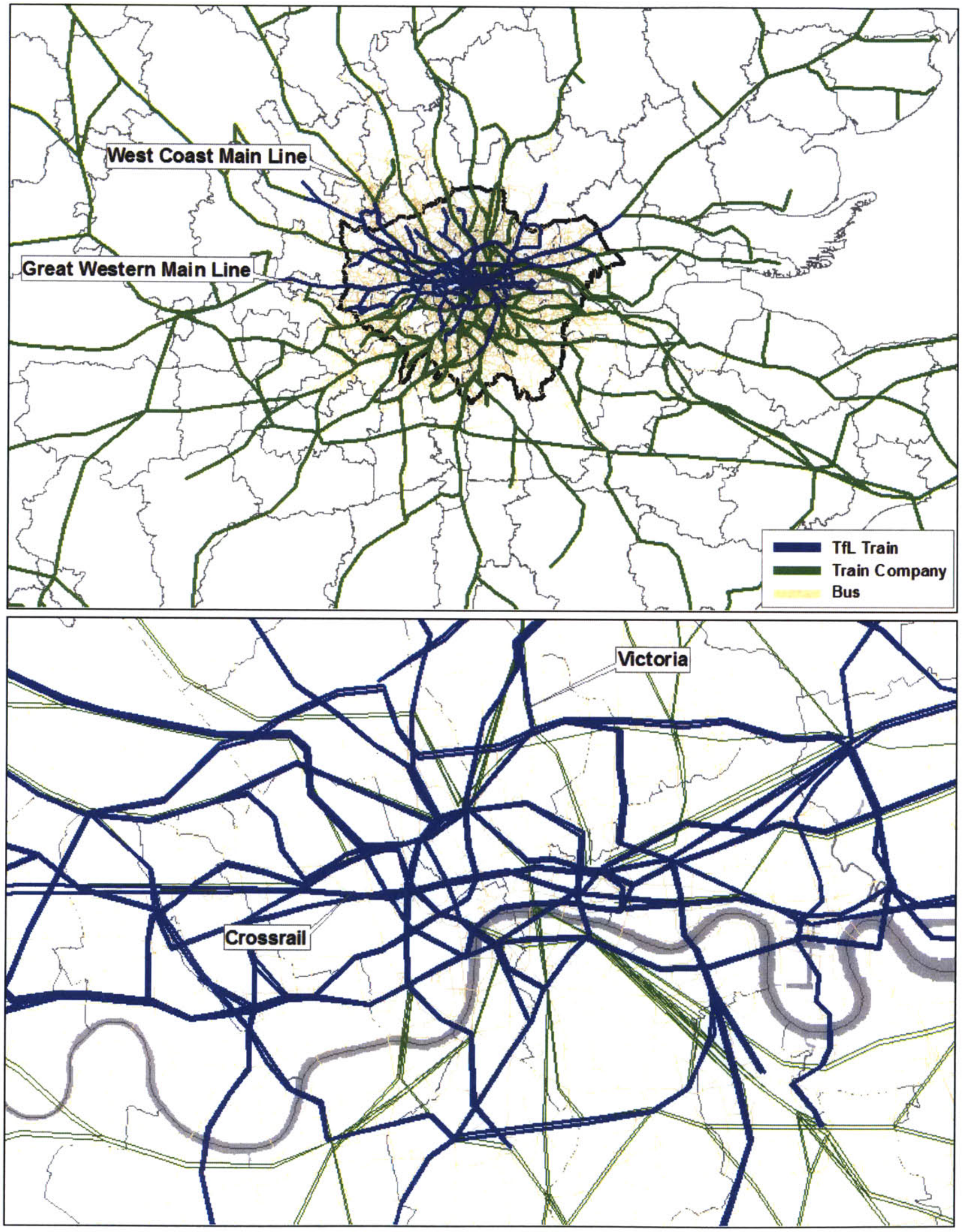
was beyond the scope of this thesis to carefully adjust bus service assumptions, and capacities were set at a very high level, the equivalent of each route running a two minute headway.

The structure of the Railplan network is presented in Figure 5-15. Public transport service, including bus routes, is well represented in and around London. Major rail routes in the southeast of England are included in the model, as are important radial bus routes. Rail routes outside of the southeast of England are either explicitly represented, or implicitly through wormholes[33].

Figure 5-16 shows rail capacity for the 2041 AM peak hour in the No Build scenario. There are a number of radial routes that provide capacity into London, including the West Coast Main Line (WCML) and the Great Western Main Line (GWML). The rail system with London functions more as a network as there are intersecting rail routes distributed throughout the city.

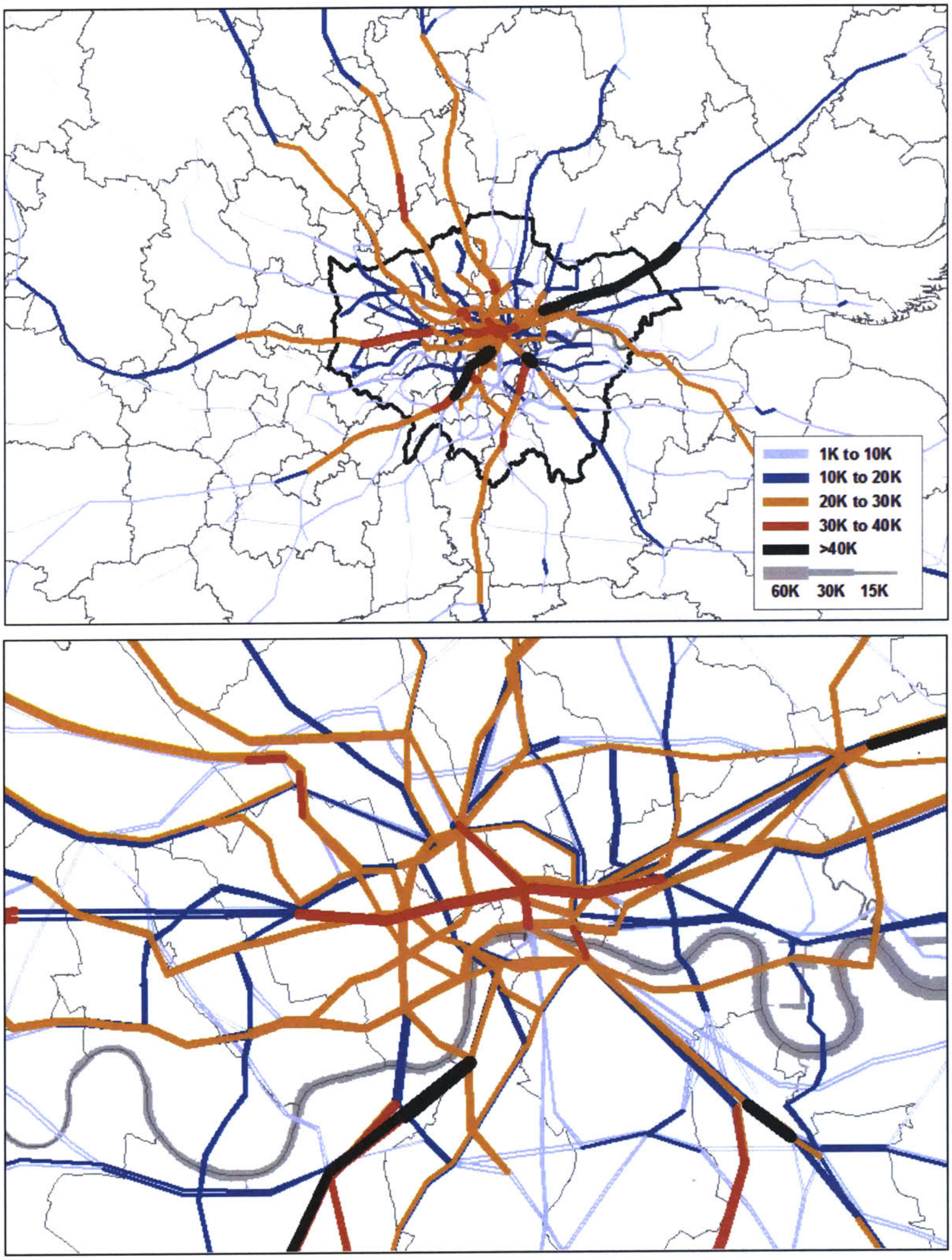
[33] A wormhole abstracts away upstream network detail. Demand is directly loaded to this point.

Figure 5-15: Public Transportation Routes in Railplan



GIS Data Source: (TfL)

Figure 5-16: 2041 AM Peak Hour Rail Capacity in No Build Scen



GIS Data Source: (TfL)

5.4 Assignment Model

A transit assignment model was developed to analyze capacity constraints in the southeast of England. The model is run in TransCAD, a commercial modeling package developed by Caliper Corporation. This section reviews the assignment process and route choice algorithm. The demand inputs are described in section 5.2 and the transportation supply inputs, such as network structure and vehicle frequencies, are described in section 5.3.

The assignment model is used for demonstration purposes. It was beyond the scope of this thesis to formally calibrate or validate the assignment model. Therefore, the model outputs should not be interpreted as forecasts. Rather, the intent of this project is to show how assignment algorithms and analysis methods can be used to evaluate capacity constraints. The assignment model was written and applied by the author. TfL bears no responsibility for the accuracy and merit of the model output.

5.4.1 Crowding Penalties

Most of the assumptions underlying the assignment algorithm, which are reviewed in section 5.4.3, were either borrowed from Railplan or are the default TransCAD parameters. However, there are a few less common steps in the algorithm. The most important modification to the assignment process is that a variable boarding penalty is applied to users attempting to board crowded vehicles. These penalties, which grow at an exponential rate as the volume over capacity (V/C) ratio approaches one, become the dominant factor in preventing V/C from exceeding one.

While this stop-based technique has been attempted in other public transport systems, including at least one effort for Railplan (see 2.1.2), it is not a common method and is not directly supported by TransCAD. This thesis also utilizes the boarding penalty in innovative ways to help analyze which land uses are most impacted by crowding.

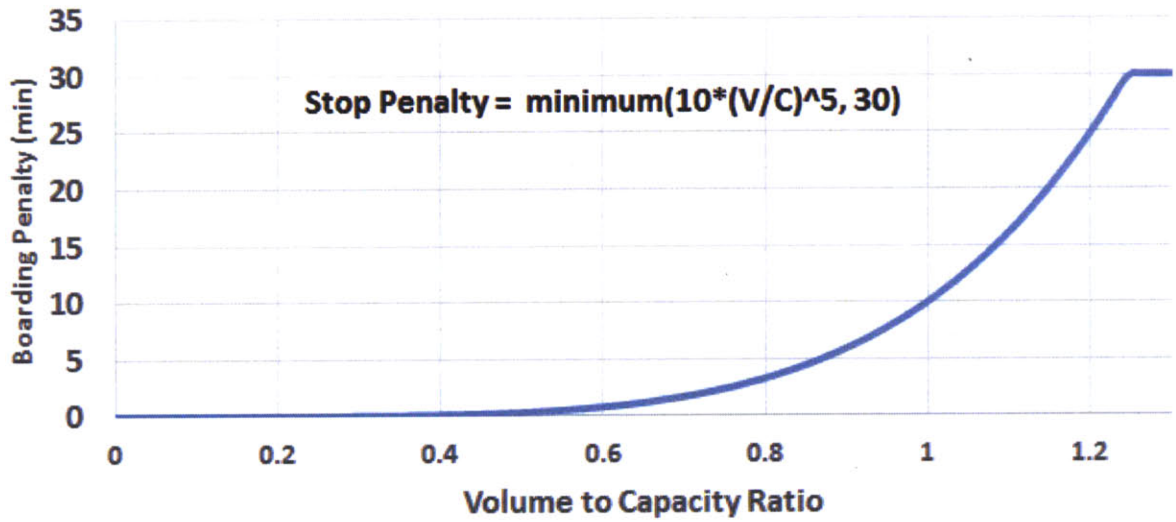
In addition to the boarding penalty, the assignment model also includes a traditional, link travel time factor (see chapter 4 for a discussion of stop versus link-based penalties). The stop-based penalty, which is only applied to users boarding the vehicle, is appropriate for representing the difficulty in boarding a vehicle and the likelihood of a denied boarding, whereas the link-based penalty, which is applied to all users that travel to the next station, is appropriate for capturing any discomfort effect in the train, as well as increased dwell times at stations.

The boarding penalty could be calibrated against observed V/C to represent both:

- The expected wait time as determined by the probability of a denied boarding,
- An extra penalty that captures the anxiety or risk of missing a train.

However, estimating this type of relationship was not feasible due to time and resource constraints and an experimental curve was developed from judgment. Figure 5-17 shows the assumed relationship between the boarding penalty and V/C. At a V/C of one, all people boarding a vehicle experience a 10 minute penalty. The penalty is capped at 30 minutes when V/C reaches approximately 1.25. The boarding penalty is capped, rather allowed to grow indefinitely, because a penalty this large likely reflects both an error in the inputs and a violation of what is appropriate for static assignment.

Figure 5-17: Boarding Penalty from Vehicle Crowding



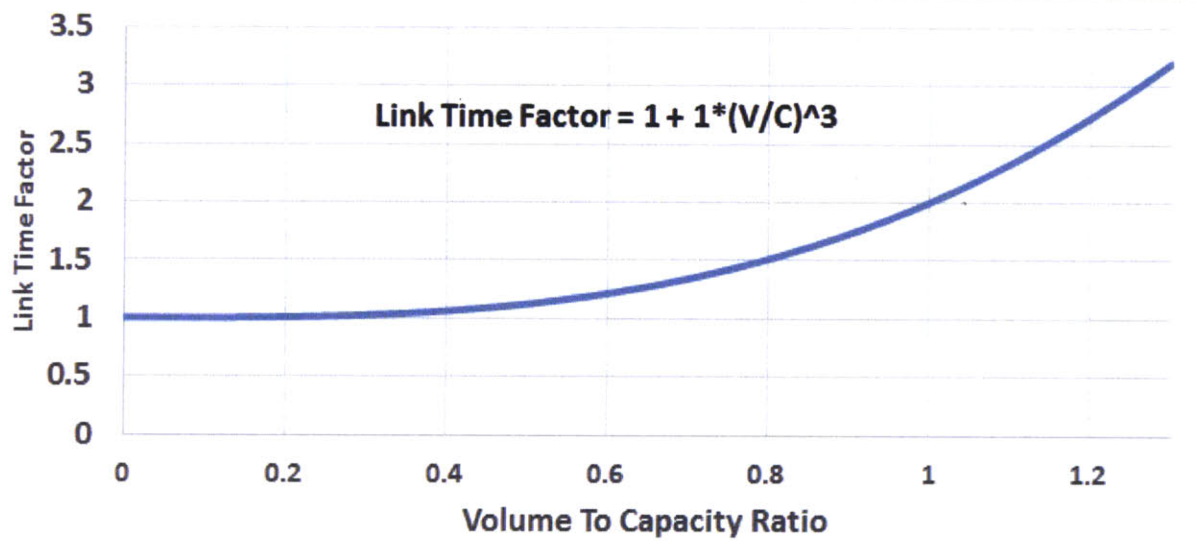
A steeper curve could have been used to grow the stop-based penalty V/C as approaches one, even approaching infinity as V/C approaches one. However, a more gradual curve was favored for a few reasons. With a gradual curve, a small change in V/C between model iterations is less likely to cause a major change in the penalty, and thereby improves stability. A second reason relates to the nature of static assignment. In static assignment, the input demand matrix is assigned even when there are no reasonable paths to avoid overloaded vehicles. The algorithmic solution is then to find an unreasonable path or completely remove the trip if it exceeds some arbitrary cost threshold. This is a clear distortion of reality because some people would either change their departure time, change mode, or may have previously found a better location to live or work.

On the other hand, by using a gradual curve, the serious challenges from public transport crowding might not be reflected in the model, and potential economic consequences could be greatly underestimated.

This assignment model attempts to adopt an intermediate position, where significant boarding penalties are applied to prevent vehicle overloading, but the penalties do not act as hard constraints and are less likely to force unreasonable paths.

Previous research has shown that train crowding levels do have an adverse effect on passenger comfort (see section 2.1.3). In the assignment model, the link-based penalty grows to a 2x factor when V/C reaches one (see Figure 5-18).

Figure 5-18: Link Penalty from Vehicle Crowding



5.4.2 Assignment Method and Parameters

TransCAD's Equilibrium Pathfinder algorithm[34] was used for transit assignment. This method can identify hyperpaths and combine service and reduce headways, and can allow for multi-path assignment when parallel routes have similar costs. This assignment method supports an iterative process where link-based crowding levels define crowding levels through MSA. This process can be run until model convergence is achieved and a negligible fraction of users change paths. The assigned demand and travel time matrices are a weighted average of each of the iterations through MSA. Because an MSA crowding process is used, and different paths between OD pairs may be selected in different iterations, the likely result is that the weighted assignment values between OD pairs incorporate several distinct paths.

[34] A formal review of this method is beyond the scope of this thesis, but its assumptions can be found in Caliper's TransCAD User's Manual

Each Pathfinder assignment was run for 20 iterations, the default value in TransCAD. The goal was not to meet a strict definition of model convergence, but to achieve modestly stable results that can be interpreted with a degree of meaning.

While the Equilibrium Pathfinder algorithm can treat the link-based penalties as variables and iteratively update their values until the model reaches convergence, the boarding penalties are invariant throughout the assignment process. The only way to treat the boarding penalties as variables, and update their values based on V/C ratios, is for the user to rebuild the transit network after each run of the Equilibrium Pathfinder algorithm.

A custom process was designed where the Equilibrium Pathfinder algorithm was run for 20 iteration to stabilize link flows, and then the stop-based penalty were updated according to Figure 5-17. Seven cycles of this process was repeated. In the second iteration, the boarding penalties were based strictly on the results from the first iteration; in the third iteration the boarding penalties were based on an equal weighting of the first and second assignment results, and after the third iteration, the penalty was made from a 1/3 weighting of the previous results, and a 2/3 weighting of all past results.

Appendix C shows the other parameters used in the assignment process. Most of the arguments used were the default values in TransCAD or based on the Railplan documentation.

5.4.3 Assignment Period

The Railplan AM assignment matrices are for 7AM to 10AM. According to the 2006 documentation, TfL relies on supply and demand curves within this three hour period to generate a weighted volume to capacity ratio for each iteration and develop new link impedance factors.

A different approach is used in this assignment model where a single one-hour peak period is assigned. 50% percent of the three-hour demand is assumed to occur in the peak-hour, and 33% of the three-hour supply is used to represent capacity.

6 METHODS TO ASSESS CAPACITY CONSTRAINTS – 2041 LONDON CASE STUDY

This chapter presents a series of analyses that explore public transport capacity constraints in 2041 the southeast of England. The chapter serves two purposes. One purpose is to review a range of analysis methods, all achievable through static assignment, to evaluate public transport capacity constraints and to consider land use implications. A few innovations on traditional methods are presented.

This review of analysis methods is done using supply and demand inputs from the 2041 "No Build" scenario. A second purpose of this chapter is then to describe expected capacity and crowding challenges in London in the No Build scenario.

6.1 Volume to Capacity Analysis

A traditional way of exploring capacity constraint in static assignment is to develop maps and tables that show V/C ratios or crowding levels. Maps showing V/C levels are particularly useful for representing the spatial location of bottlenecks in the system.

The primary strength of V/C maps and tables is that they are often easy to produce, convey a large amount of information, and are relatively easy to explain to non-technical audiences. This method can be effective when the goal is to argue that transportation supply is insufficient to meet unconstrained demand.

Figure 6-1 shows which lines are expected to suffer from the worst crowding conditions in the southeast of England. The lines in black are at the maximum, crowding level of an average of 4 people per square meter for the whole train. The tabular analysis (see Table 7-1) confirms that there are several links, such as the one along Victoria Line southbound (VLSB) and Northern Line northbound that are loaded past this point. Outside of London, a number of radial commuter routes, especially from the southwest are loaded close to capacity. At face value, these results suggest that the rail system is under heavy stress, and there may be routes that cannot cope with further growth.

However, the crowding map might actually understate how bad the level of service will be for some routes. The crowding level presented in Figure 6-1 is an average of all routes that share the infrastructure. Therefore, certain routes sharing the infrastructure could be loaded past the average. A table of V/C ratios, such as presented in Figure 7-2, can show the crowding levels by individual route in more detail. This table, which shows the percent of links along a given route that are below a given V/C ratio, indicates that there are a number of routes, such as Crossrail eastbound (XREB) and WCML that were not flagged in the map for displaying maximum crowding, but contain segments that are loaded beyond the maximum level.

While standard V/C analysis is useful for identifying problematic links in the network, the approach does not (directly) reveal which land uses are contributing to the problem and which ones are most threatened by further growth. For example, it is not immediately clear which land uses to the north of central London are contributing to crowding on VLSB, and which land uses in central London are most threatened by crowding on VLSB.

Figure 6-1: Link Crowding in No Build Scen

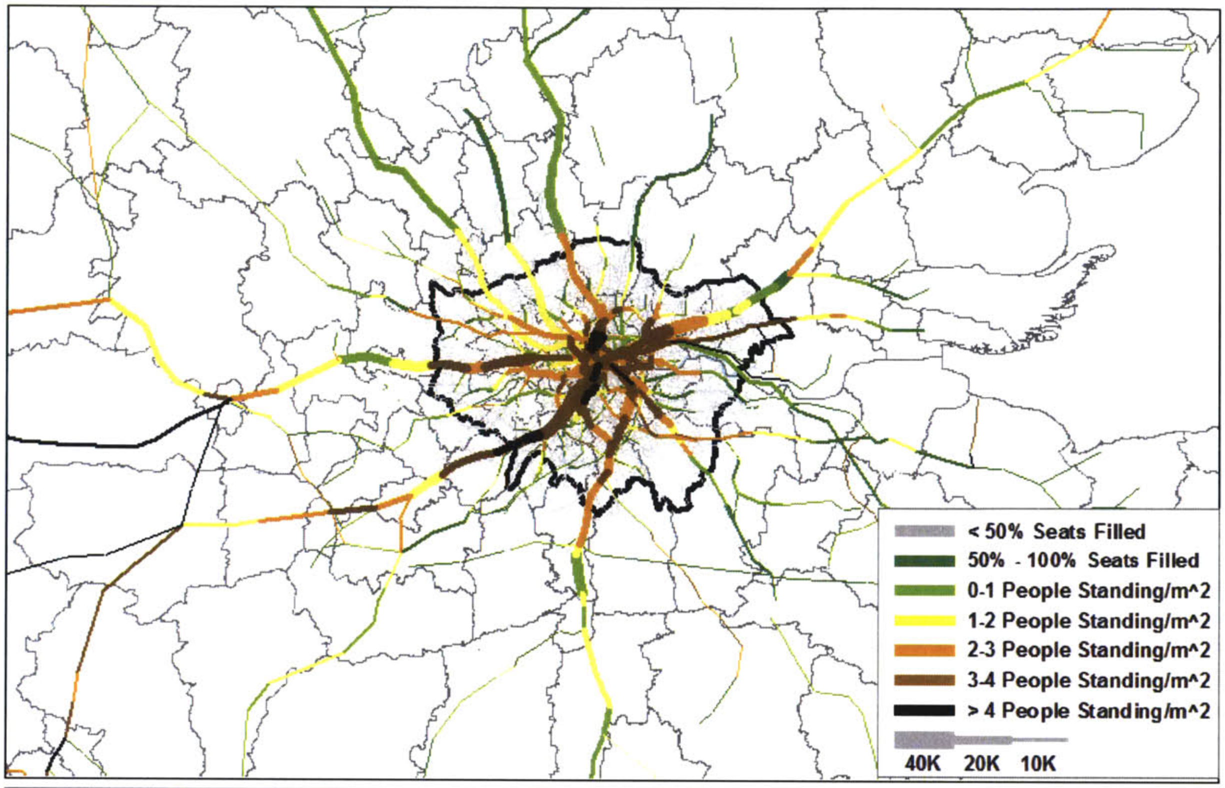


Table 6-1: V/C Ratio Distribution of Stops in No Build Scen

Line	Stops	% Stops below Volume/Capacity Ratio					
		< .25	< .5	< .7	< .9	< 1	< 1.1
Lines Into Euston	251	41.4%	53.0%	67.3%	84.5%	94.4%	98.8%
Victoria SB	27	22.2%	33.3%	51.9%	63.0%	85.2%	100.0%
Northern Bank SB	89	18.0%	53.9%	65.2%	91.0%	100.0%	100.0%
Northern Charing SB	56	12.5%	30.4%	48.2%	85.7%	100.0%	100.0%
Piccadilly SB	266	27.8%	56.4%	73.3%	83.1%	94.7%	100.0%
Crossrail EB	179	52.0%	67.0%	79.9%	93.9%	97.8%	99.4%
Hammersmith, Circle, Metropolitan EB	155	12.9%	38.7%	63.2%	100.0%	100.0%	100.0%
Other Underground	2779	34.7%	60.1%	78.9%	92.8%	99.4%	100.0%
DLR	159	13.2%	66.7%	88.7%	100.0%	100.0%	100.0%
Other Overground	282	16.3%	55.7%	83.0%	98.2%	100.0%	100.0%
Other TOC	8057	31.2%	56.7%	73.4%	87.0%	91.9%	95.3%

6.2 Select Link Analysis

Select link analysis can complement volume over capacity analysis and show which trips and land uses contribute to bottlenecks. In select link analysis, the analyst chooses one or more network links or nodes to review, and a report is generated on the origin, destination, and path of all flow that crosses (some combination of) these links or nodes. A full select link analysis usually generates two data sets:

1. A matrix that records the flow between each OD pair that crosses the selected links and nodes.
2. A table that reports the amount of flow assigned to each link in the network that crosses the selected links or nodes at any point.

Full select link analyses can require long processing times and generate a lot of data, especially when multiple links are queried. Long computer processing time can make it impractical to look at all the bottlenecks in the London public transport system through a full select link analysis. However, it is possible to do a pseudo-select link analysis where only a matrix is generated of the demand between OD pairs that go through the chosen links and nodes. These data can be generated within a small multiple of the time needed to perform a regular assignment.

A pseudo-select link analysis was performed to examine which trips land uses contribute to and are affected by public transport crowding in the southeast of England. The method used in this research resembles what Buchanan and Volterra did for Crossrail to examine the share of travel time going to the

City of London and Isle of Dogs at different levels of crowding (see section 2.3.3). These data are particularly useful for assessing the level of discomfort in traveling between OD pairs. A rising level of discomfort could force businesses to pay a wage premium or even cause them to rethink location decisions.

This chapter also presents an innovation over what was done for Crossrail. The percent of trips between an OD pair that either pass through a bottleneck, defined as any link with a volume to capacity ratio over .9, or board into a bottleneck is reported. OD pairs that send flow through a bottleneck are at least exacerbating network problems. If a low percentage of travel time is spent in the bottleneck, as indicated from the share of travel time at each V/C level, then the OD pair could be exacerbating the crowding problem without experiencing adverse effects. However, if a large percentage of the travel time occurs in the bottleneck, then the OD pair is contributing to the problem without experiencing adverse effects.

OD pairs that require a transfer in a bottleneck are in an especially precarious position. If network crowding grows more severe, then traveling during the peak may become unacceptable and more and more users will have to consider alternative strategies – such as traveling earlier or later in the day or switching modes. If coupled with long, in-vehicle times in crowding conditions, then the OD pairs are at risk for crowding to have an adverse economic impact.

Table 6-2 shows this select link analysis for the southeast of England. On the origin end, the Commuter Ring appears to both exacerbate and be threatened by public transport crowding. About 70% of the trips starting in the Commuter Ring cross a bottleneck at some point, nearly 15% of trips need to board into a bottleneck, and about 20% of travel time is spent at a volume to capacity ratio of over .9. Dacorum, located in Hertfordshire to the immediate northwest of London, stands out for having a large fraction of public transport trips boarding into a bottleneck. This means that assumed growth in this district could be threatened from crowding.

On the destination end, more than half of the demand going into central London crosses a bottleneck, and over 20% of travel time is spent at a V/C ratio of over .9. This shows a high level of public transport crowding heading into central London.

Table 6-2: Select Link V/C Distribution in No Build Scen

	% TIME AT VOLUME/CAPACITY RATIO						% Thr Bottle	% Brd Bottle
DESTINATIONS	<.25	<.5	<.7	<.9	<1	<1.1	Perc	Perc
City of London	10.2%	29.5%	56.6%	77.1%	87.5%	95.1%	58.2%	11.2%
Central London	10.6%	31.1%	57.4%	77.3%	87.7%	94.4%	59.0%	12.2%
Isle of Dogs	10.6%	29.0%	58.0%	80.1%	89.2%	95.2%	61.6%	9.9%
Inner London- Ring	24.4%	49.7%	71.6%	85.4%	91.7%	95.8%	35.3%	6.3%
Inner London-All	16.1%	38.5%	63.0%	80.5%	89.3%	95.0%	48.8%	9.7%
Outer London-Ring	54.5%	79.6%	90.1%	95.2%	97.6%	99.0%	13.0%	1.7%
London-All	23.0%	45.9%	67.9%	83.1%	90.8%	95.7%	41.3%	8.0%
ORIGINS	<.25	<.5	<.7	<.9	<1	<1.1	Perc	Perc
Inner London	29.9%	62.6%	85.2%	94.1%	98.3%	99.6%	22.8%	4.2%
Outer Ring	32.1%	56.8%	76.6%	90.7%	97.5%	99.7%	39.3%	2.5%
Commuter Ring	19.8%	36.7%	61.1%	79.4%	89.8%	96.0%	73.8%	15.8%
Camden	29.2%	67.8%	87.8%	96.7%	99.6%	99.6%	17.1%	0.9%
Croydon	29.1%	56.7%	74.8%	87.2%	92.5%	99.2%	56.0%	13.3%
Ealing	34.5%	63.1%	84.3%	97.8%	99.5%	99.8%	15.6%	0.1%
Enfield	37.9%	66.6%	79.0%	86.0%	94.6%	100.0%	45.1%	1.4%
Greenwich	31.8%	61.0%	85.5%	96.1%	99.7%	99.9%	17.1%	5.1%
Hackney	29.1%	70.1%	92.9%	95.9%	98.7%	99.9%	14.4%	2.9%
Hammersmith	30.0%	61.1%	87.2%	98.5%	99.3%	99.3%	5.4%	2.2%
Harrow	38.6%	58.1%	83.5%	95.9%	99.5%	99.6%	19.8%	0.0%
Havering	29.0%	50.6%	72.6%	90.7%	99.7%	100.0%	48.7%	0.8%
Merton	30.3%	54.6%	71.7%	85.7%	93.8%	99.6%	55.4%	1.0%
Newham	28.1%	46.6%	69.2%	89.9%	99.6%	99.6%	40.5%	8.1%
Richmond	23.6%	55.1%	75.4%	98.4%	99.9%	100.0%	19.7%	0.0%
Southwark	32.8%	71.6%	95.1%	98.5%	99.8%	99.8%	8.6%	3.1%
Dacorum	23.8%	37.8%	60.2%	78.9%	91.9%	97.5%	81.3%	47.3%
Dartford	22.8%	45.7%	74.5%	95.2%	97.8%	99.5%	54.0%	2.0%
Epsom and Ewell	23.8%	38.4%	66.9%	88.8%	96.7%	99.9%	70.0%	0.0%
Slough	17.7%	37.6%	60.2%	83.8%	94.6%	97.6%	81.3%	5.6%
Watford	49.9%	66.4%	88.2%	95.1%	99.7%	100.0%	27.0%	0.7%
Welwyn Hatfield	9.3%	23.9%	44.4%	70.6%	90.0%	99.4%	95.5%	19.6%
Wycombe	13.1%	42.8%	59.4%	70.8%	87.6%	91.7%	93.8%	13.5%

Thr = through; Brd = Board; Bottle = Bottleneck

Desire lines can be used to present a two-dimensional representation of the select link analysis. This two-dimensional representation indicates that for a given destination (origin), only a subset of origins (destinations) are contributing to the crowding problem, an important fact that is not immediately clear when analyzing a table.

Figure 6-2 shows the number of trips between OD pairs that need to board or transfer in a bottleneck. While districts in the commuter ring, such as Dacorum, are predicted to have a relatively high percentage of trips that need to board in a bottleneck (see Table 6-2), Figure 6-2 indicates that OD pairs in London, such as Islington to Westminster, require the highest number of total trips to board in a bottleneck.

Figure 6-2: Trips that Board in a Bottleneck

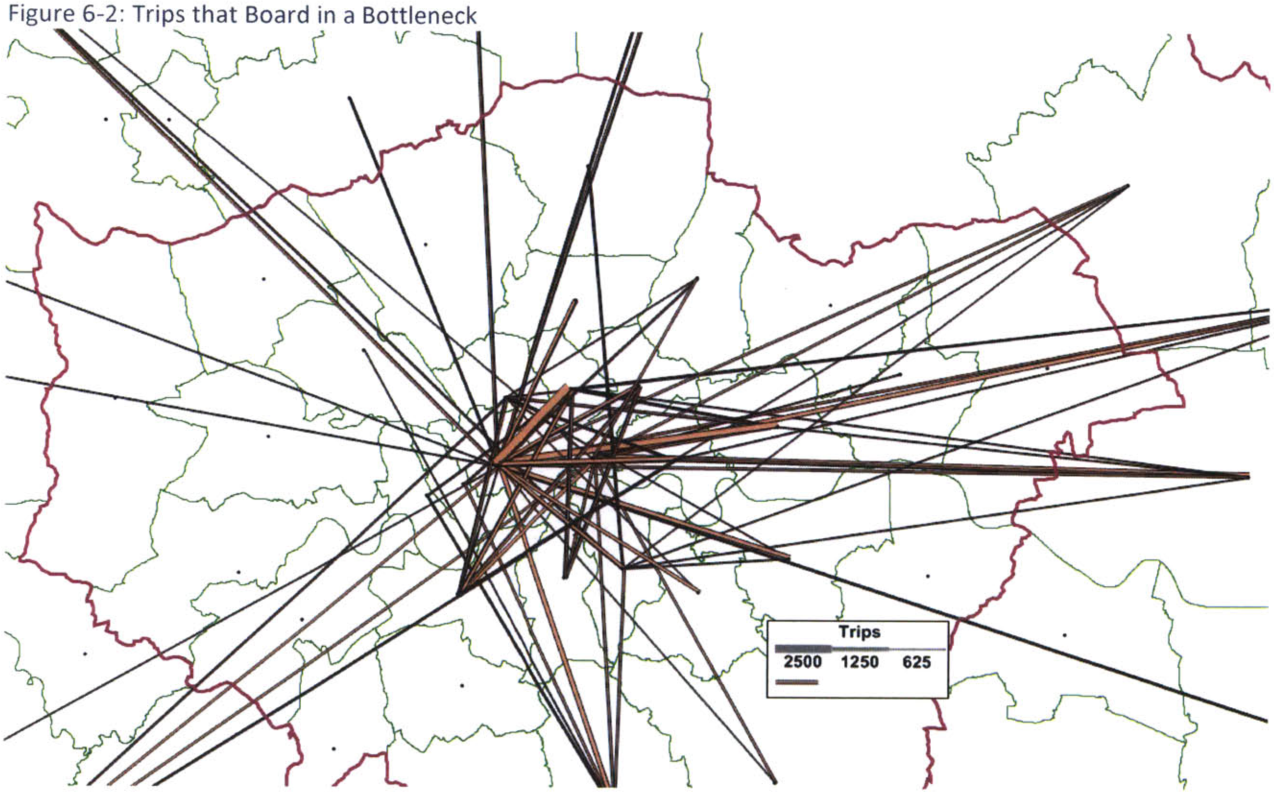
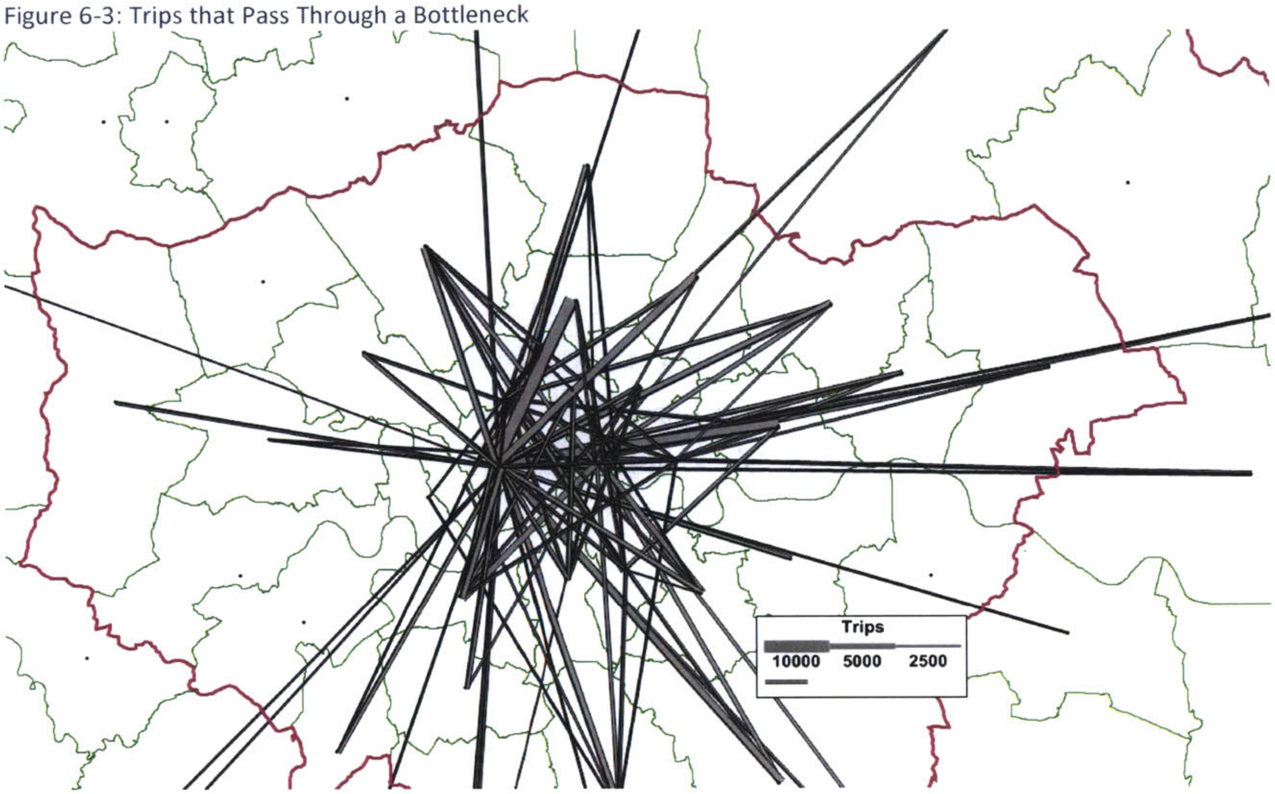


Figure 6-3 shows the number of trips that pass through a bottleneck. Haringey sends over 10,000 trips through a bottleneck to Westminster, potentially exacerbating crowing problems for other ODs in central London.

Figure 6-3: Trips that Pass Through a Bottleneck



6.3 Cordon Capacity

Cordon capacity measures can be used to explicitly compare the flow into (or out) of district against the maximum supply. When crowding reaches severe levels, the cordon capacity measure can make a compelling argument for the impossibility or difficulty of further growth. As was done for the Crossrail business case, the cordon capacity measure can also be used to argue that transportation is a binding constraint on growth.

However, the cordon capacity measure suffers from a number of weaknesses and can even understate crowding levels. Whenever there is more than one access path to a district, then it is almost certainly the case that one of the paths is worse than the others. There may even be an access path that has a low V/C ratio, even if the others have higher ratios. But the total public transport supply in the cordon capacity measure will include these less crowded paths, and offset problems from crowded paths. This type of bias is less prevalent in select link analysis, where the crowding estimates are weighted by flow to the district.

The cordon capacity measure also does not say whether there are crowding problems within or outside of the cordon. If the more significant bottleneck lies within this cordon, then this will be entirely missed by the measure. In the HS2 case, adding capacity to the London cordon may only be helpful in so far as there are not worse bottlenecks on the roads and the rest of public transport system.

Table 6-3 shows the cordon capacity measure for districts in the southeast of England. Considering the aforementioned weaknesses of the cordon measure, the V/C ratio into central London and the Isle of Dogs is quite high, at nearly 75%. Analyzing other districts is challenging because it is not immediately clear whether a lower cordon capacity V/C value suggest that there are no problems, or whether there is a mixture of lightly used access routes and heavily used access routes. In the latter case, a low or medium cordon capacity V/C would not draw attention to problems from the heavily used access route.

Table 6-3: Cordon Capacities in No Build Scen

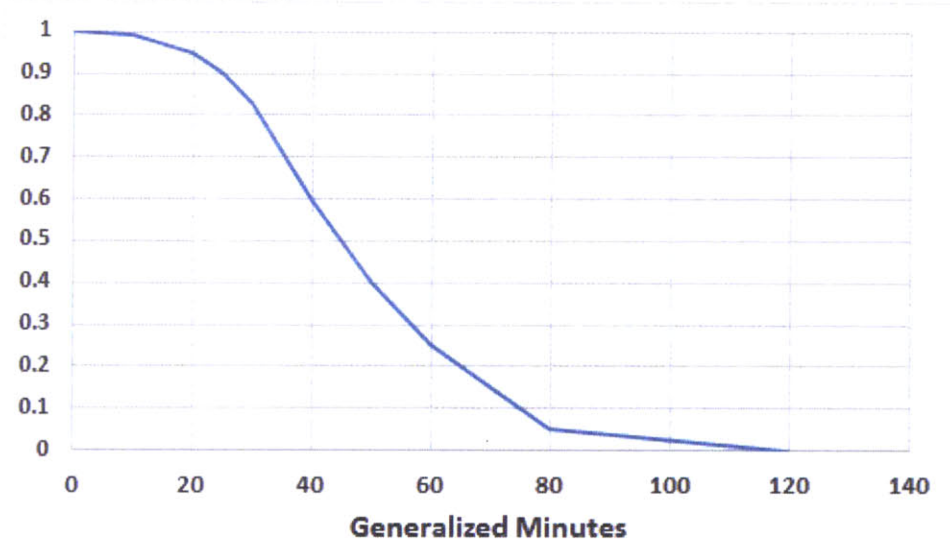
	All Trains			Excluding TOCs		
	Demand	Supply	VoC	Demand	Supply	VoC
Central London	749,816	1,021,692	73.4%	413,733	566,626	73.0%
Inner London	596,205	924,931	64.5%	263,372	453,100	58.1%
London	259,832	400,260	64.9%	19,376	59,777	32.4%
Isle of Dogs	87,780	114,728	76.5%	66,881	80,012	83.6%
Camden	311,060	517,828	60.1%	252,552	403,475	62.6%
City of London	312,669	473,685	66.0%	192,392	271,626	70.8%
Croydon	45,636	90,411	50.5%	1,850	2,812	65.8%
Ealing	50,724	145,893	34.8%	48,630	140,177	34.7%
Enfield	18,871	68,768	27.4%	1,759	27,948	6.3%
Greenwich	49,226	147,389	33.4%	24,085	62,009	38.8%
Hackney	56,494	118,981	47.5%	41,283	85,422	48.3%
Hammersmith	102,768	220,493	46.6%	100,638	215,886	46.6%
Harrow	30,342	104,981	28.9%	22,977	90,870	25.3%
Havering	21,431	72,089	29.7%	6,276	50,270	12.5%
Merton	38,325	101,064	37.9%	5,378	33,273	16.2%
Newham	126,894	284,091	44.7%	90,462	210,271	43.0%
Richmond	15,021	47,132	31.9%	2,896	9,943	29.1%
Southwark	207,769	378,252	54.9%	91,535	150,254	60.9%
Sutton	16,741	37,855	44.2%	0	0	0.0%
Tower Hamlets	211,921	345,320	61.4%	170,353	268,811	63.4%
Waltham Forest	28,191	74,548	37.8%	27,912	71,131	39.2%
Westminster	410,910	577,856	71.1%	335,885	475,090	70.7%
Dacorum	4,215	8,872	47.5%	0	0	0.0%
Dartford	7,410	23,184	32.0%	0	0	0.0%
Epsom and Ewell	8,876	17,978	49.4%	0	0	0.0%
Slough	5,961	19,612	30.4%	3,244	12,002	27.0%
Watford	10,304	26,742	38.5%	1,313	11,071	11.9%
Welwyn Hatfield	6,416	19,886	32.3%	0	0	0.0%
Wycombe	2,670	6,783	39.4%	0	0	0.0%

6.4 Accessibility Analysis

Accessibility analysis is not traditionally performed by incorporating measures of capacity constraint, but it is an important consideration because accessibility is often employed as an input into land use models that forecast household, business, and developer decisions. While the other capacity measures, volume over capacity, select link, and cordon capacity, may be easier for analysts to interpret and explain, the change in accessibility level may be what is ultimately used to predict wider economic impacts.

Two accessibility measures were developed for the southeast of England. An accessibility measure that looks at the ease of reaching jobs from an origin perspective, and an accessibility measure that looks at the ease of receiving people from a destination perspective. The first measure, which is weighted by jobs, is appropriate for considering the attractiveness of a location from a resident's perspective. The second measure, which is weighted by people, is appropriate for considering the attractiveness of a location from a business's perspective. Figure 6-4 shows the accessibility weights used as a function of generalized cost in weighted minutes. The accessibility weights were assumed and are intended for demonstration purposes. The weighted minutes include any link-based or stop-based crowding penalties, as well as travel time factors applied to walking and waiting times (see appendix C).

Figure 6-4: Gravity Weights



Due to incomplete public transport travel data and limited access and egress walk time assumptions, the accessibility analysis did not consider people and jobs outside of southeast London. The accessibility analysis also did not consider business-to-business access. The potential for business-to-business interactions clearly affects location decisions, but crowding may be less important for business trips than for commuter trips because business travel often takes place outside of the peak. However inter-city business travelers, such as HS2 passengers, might arrive during the peak and would be sensitive to crowding levels. Furthermore, developing an appropriate curve for employment-to-employment accessibility can be difficult. The curve would need to place a lot of weight on the potential for short business trips for which there may not be suitable data.

Figure 6-5 shows an accessibility map for the southeast of England. The top half of the maps shows the household perspective, weighted by jobs, while the bottom half shows the business perspective, weighted by people. Because the London public transport network is dense and most of the jobs are concentrated in central London, transit accessibility generally declines as a function of distance from the center of the city. However, there are clear cases where land uses have a worse accessibility level than immediate neighbors, such as Old Oak Common, as well as clear cases where land uses have a better accessibility than immediate neighbors, such as Stratford.

Table 6-4 shows an aggregation of the accessibility data to the district level. Central London and City of London enjoy the best accessibility to people. Southwark, which benefited from the JLE and was one of the faster growing districts from 2000 to 2010 (see Table 5-2), has a noticeably higher level of accessibility among districts south of the Thames. The weighted accessibility level to jobs from the Commuter Ring is much lower than inside of London.

Among the development sites in London, Euston and King's Cross stand out as having the best accessibility level to people, at a level comparable to the City of London. This result offers promise that a redeveloped Euston could be an attractive location for businesses. Without access to Crossrail in the No Build scenario, Old Oak Common's accessibility level is relatively poor. The fact that road connectivity is also poor further highlights Old Oak Common's development challenges.

Figure 6-5: Disaggregate Accessibility in No Build Scen

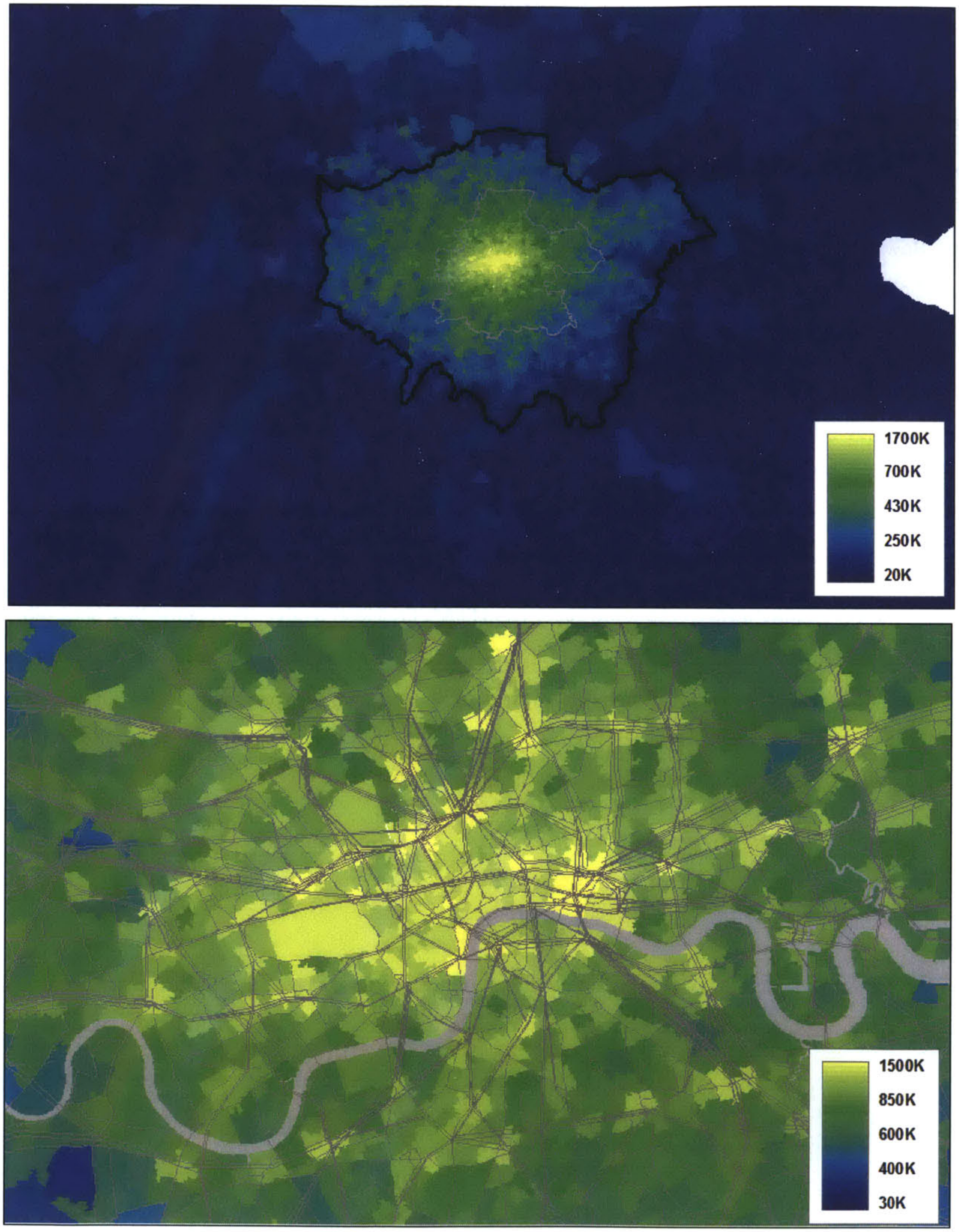


Table 6-4: Aggregate Accessibility in No Build Scen

	Jobs	People
Central London	1,474,130	1,357,090
Isle of Dogs	740,446	1,018,140
Inner London- Ring	719,364	987,009
Inner London-All	769,344	1,173,585
Outer London-Ring	348,794	578,891
London-All	514,663	930,636
Camden	1,016,414	1,297,040
City of London	1,683,665	1,467,144
Croydon	260,139	578,709
Ealing	477,501	693,024
Enfield	312,346	551,515
Greenwich	365,014	618,263
Hackney	822,855	1,113,287
Hammersmith	765,102	952,382
Harrow	378,306	604,725
Havering	259,416	478,183
Merton	404,899	731,239
Newham	509,654	847,693
Richmond	342,139	535,824
Southwark	864,979	1,091,025
Dacorum	74,231	196,268
Dartford	79,325	136,463
Epsom and Ewell	93,941	223,669
Slough	133,800	252,226
Watford	212,682	360,881
Welwyn Hatfield	145,480	322,982
Wycombe	8,759	20,777

Table 6-5: Accessibility of Development Sites in No Build Scen

Development Site	Jobs	People
Old Oak Common	383,205	401,988
Euston	1,586,757	1,508,807
Kings Cross	1,534,631	1,544,135
Stratford City	888,794	1,382,087
White City	574,311	580,855
The Royals	474,941	686,982
Canary Wharf	1,022,020	1,183,024
Silvertown Quay	517,195	831,764
Greenwich Peninsula	518,892	783,810
Ruskin Square	371,995	815,105
9 Elms	831,651	843,772
Earls Court	1,058,895	1,173,292
Chiswick Park	635,688	816,986
Waterloo	1,529,905	1,272,183
Paddington	1,488,046	1,425,416
Wembley	425,955	648,333

7 DISTORTIONS IN ECONOMIC ANALYSIS FROM THE IMPROPER ENFORCEMENT OF CAPACITY CONSTRAINTS

In public transport assignment, an exponentially increasing penalty may be applied to discourage users from boarding crowded vehicles. However, if the penalty does not grow to a significant level as V/C approaches one, or if the penalty is applied to all public transport users, not just those boarding the vehicle, then the model output may contain distortions that would bias economic analysis. The most significant bias would occur for OD pairs where the preferred path[35] includes a difficult transfer.

In some cases, the error in enforcing capacity constraint may lie entirely with the analyst and not with the model. Even if the available model can do a reasonable job of enforcing capacity constraint, if the analyst studies travel measures that disregard capacity, then the economic analysis will be biased. One clear case is when measuring accessibility, which can be an important factor.in making investment decisions, as it was the case for Crossrail. The isochrone accessibility measure, which is often calculated using unweighted travel times, becomes insensitive to crowding levels. Basing investment on this type of measure would bias policy makers towards favoring projects that connect new land uses to the public transport system, and would ignore the benefit of adding capacity to land uses that already have strong connections to the network.

This chapter considers some, but not all, of the adverse effects from crowding in public transport systems. The most important omission is that there is no attempt to explicitly represent how dwell times increase as crowding grows worse. At first, this increase in dwell time would simply make everyone's journey a little longer. Eventually, the increase in dwell time could grow large enough to decrease the maximum vehicle throughput and therefore the system capacity. Although not explored in this thesis, it is entirely possible that maximum passenger throughput could go down if too many people are allowed to try to board the train, thus greatly increasing dwell times. While there are ways to include a dwell time effect in frequency-based models that are appropriate for long-range planning, explicitly modeling service irregularities may require dynamic, schedule-based models.

[35] The 'preferred path' is assumed to be the path that a user would take if crowding were not a significant impediment

The first section of this chapter looks at the effects of not enforcing capacity constraint altogether, and the second section explores the effects of not including a stop-based effect.

7.1 No Crowding Deterrent

This section examines the effect of omitting a capacity constraint and crowding feedback. Omitting the crowding penalty was not strictly required for this analysis. A similar violation of capacity constraint could be demonstrated if a modest penalty had been used instead of no penalty.

7.1.1 Link Volumes

If there is no crowding deterrent, then the economic value of preferred paths in the public transport system will be overstated. Some flow will be allowed to use the preferred path, instead of being shifted to another path, re-assigned to a different mode, or departing at a different time in the day. Figure 7-1 shows the change in network flow when all crowding effects are removed the 2041 No Build scenario. This graph shows a noticeable shift in demand from bus routes to major Underground routes, such as VLSB and Northern Line Bank Southbound (NLBSB).

Table 7-1 looks at the new V/C ratio for stops. Many links have volumes well in excess of capacity. Nearly 50% of the stops on VLSB, and over 30% of the stops on NLBSB exceed the capacity limit. This result suggests that the economic benefit of schemes that provide parallel capacity to major routes, such as VLSB, would be greatly underestimated if capacity constraints are not properly enforced.

Figure 7-1: Change in Network Flow from No Build Scen to Unconstrained Scen

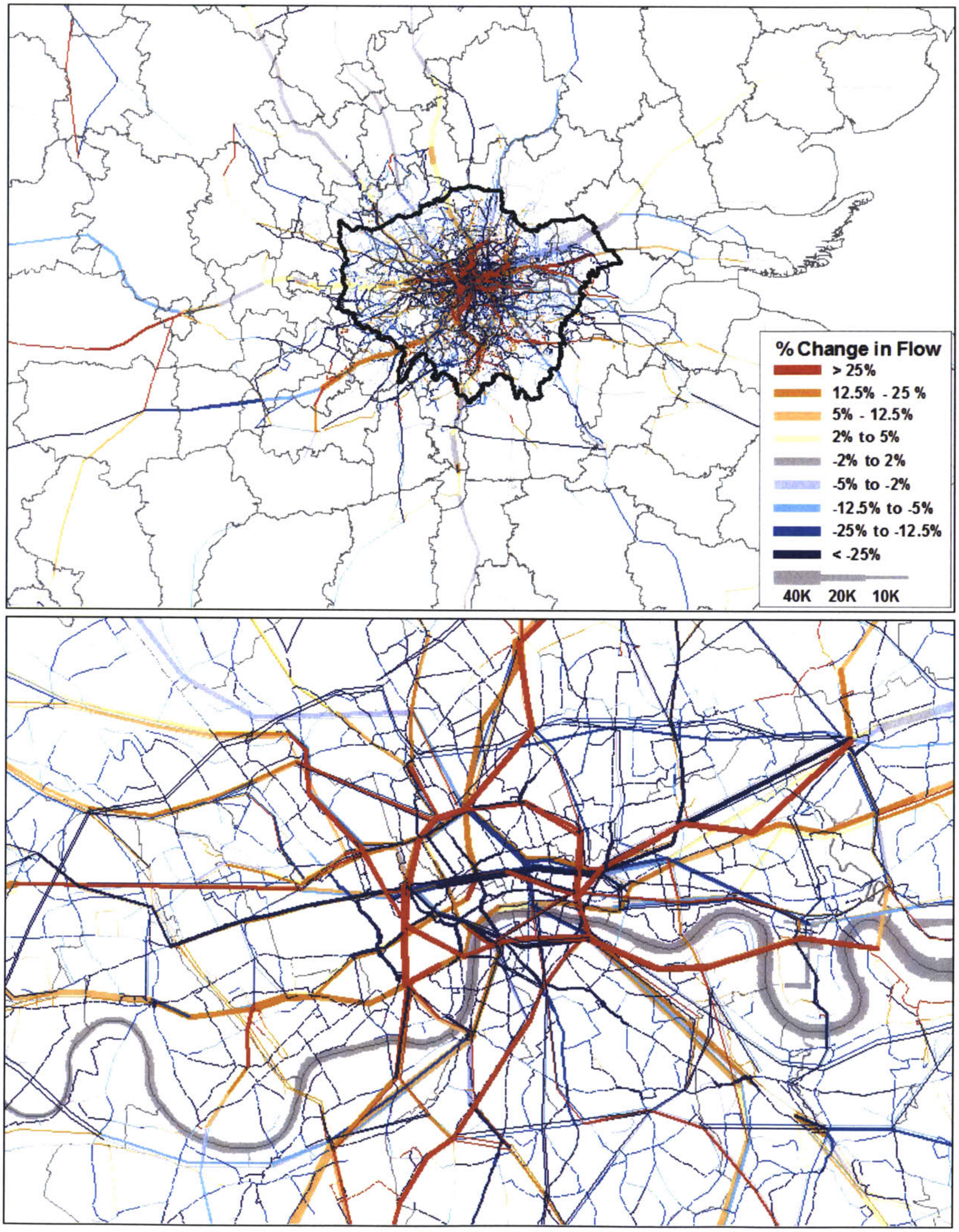


Table 7-1: V/C Ratio Distribution of Stops in Unconstrained Scen

Line	Stops	% Stops below Volume/Capacity Ratio					
		<.25	<.5	<.7	<.9	<1	<1.1
Lines Into Euston	251	55.8%	71.3%	76.5%	82.1%	83.3%	84.9%
Victoria SB	27	14.8%	29.6%	37.0%	44.4%	51.9%	59.3%
Northern Bank SB	89	14.6%	53.9%	61.8%	65.2%	68.5%	73.0%
Northern Charing SB	56	17.9%	33.9%	64.3%	82.1%	94.6%	100.0%
Piccadilly SB	266	27.1%	53.8%	69.2%	77.8%	83.8%	90.2%
Crossrail EAST	179	58.1%	66.5%	81.0%	87.2%	90.5%	92.2%
Hammersmith, Circle, Metropolitan EB	155	20.0%	44.5%	65.8%	87.7%	95.5%	100.0%
Other Underground	2779	36.7%	65.2%	79.0%	83.3%	86.2%	88.9%
DLR	159	30.8%	76.7%	89.9%	97.5%	99.4%	100.0%
Other Overground	282	27.7%	75.2%	86.5%	90.1%	90.1%	92.2%
Other TOC	8057	39.1%	63.8%	79.6%	84.4%	87.1%	89.3%

Table 7-2: Change in V/C Ratio Distribution of Stops from No Build Scen to Unconstrained Scen

Line	Δ Stops	Δ % Stops below Volume/Capacity Ratio					
		<.25	<.5	<.7	<.9	<1	<1.1
Lines Into Euston	0	↑ 14.3%	↑ 18.3%	↑ 9.2%	↓ -2.4%	↓ -11.2%	↓ -13.9%
Victoria SB	0	↓ -7.4%	↓ -3.7%	↓ -14.8%	↓ -18.5%	↓ -33.3%	↓ -40.7%
Northern Bank SB	0	↓ -3.4%	0.0%	↓ -3.4%	↓ -25.8%	↓ -31.5%	↓ -27.0%
Northern Charing SB	0	↑ 5.4%	↑ 3.6%	↑ 16.1%	↓ -3.6%	↓ -5.4%	0.0%
Piccadilly SB	0	-0.8%	↓ -2.6%	↓ -4.1%	↓ -5.3%	↓ -10.9%	↓ -9.8%
Crossrail EAST	0	↑ 6.1%	-0.6%	↑ 1.1%	↓ -6.7%	↓ -7.3%	↓ -7.3%
Hammersmith, Circle, Me	0	↑ 7.1%	↑ 5.8%	↑ 2.6%	↓ -12.3%	↓ -4.5%	0.0%
Other Underground	0	↑ 2.1%	↑ 5.1%	0.0%	↓ -9.5%	↓ -13.2%	↓ -11.1%
DLR	0	↑ 17.6%	↑ 10.1%	↑ 1.3%	↓ -2.5%	-0.6%	0.0%
Other Overground	0	↑ 11.3%	↑ 19.5%	↑ 3.5%	↓ -8.2%	↓ -9.9%	↓ -7.8%
Other TOC	0	↑ 7.9%	↑ 7.0%	↑ 6.1%	↓ -2.6%	↓ -4.8%	↓ -6.0%

7.1.2 Accessibility

Accessibility is commonly measured without incorporating crowding effects and capacity constraints, even though crowding is a deterrent to travel, and full vehicles are an outright deterrent to travel. One reason for this omission is to provide a simple measure that is easy to interpret and explain to non-technical audiences (see section 2.2). Among accessibility measures that contain a land use component, the unweighted isochrone measure is arguably the easiest for analysts to interpret and explain to non-technical audience. However, the unweighted isochrone measure cannot include a crowding or capacity component because the measure is strictly a function of uncongested travel times between OD pairs. A strict reliance on this measure in economic analysis would minimize the benefit of capacity investment.

Figure 7-2 shows the change in accessibility when no crowding effect is modeled[36]. In almost all cases, the predicted level of accessibility is much higher, often in excess of 100% when crowding effects are not included, with some zones being disproportionately affected. For the change in access to jobs from the household perspective, which is shown in the top half, zones outside of Inner London experience greatest increase in accessibility, from the business perspective, shown in the bottom half, zones in Inner London experience the greatest increase in accessibility. One simple explanation for this asymmetry may be that people already living inside of Inner London pass through fewer bottleneck to reach businesses, but businesses inside of Inner London require people to pass through bottlenecks to get there.

The aggregate effect of omitting crowding effects is shown in Table 7-3. The accessibility level of a number of districts in the Commuter Ring, such as Dacorum and Waycombe, show a strong improvement in terms of access to jobs. The accessibility level from people in Central London is over 60% higher when crowding is not modeled, whereas the accessibility level in Outer London is 30% higher. This result suggests that ignoring crowding and capacity in accessibility could introduce significant spatial biases.

Euston shows a relatively large change in access from households when crowding effects are removed (see Table 7-8), suggesting that a failure to consider capacity constraint could bias its attractiveness in economic analysis. The Canary Wharf and Greenwich peninsula sites also show large changes in access from households. The Ruskin square development sites shows a large increase in access to jobs.

[36] To minimize noise, in Figure 7-2 and in other disaggregate accessibility maps, only zones with an accessibility to jobs of over 10,000 are used.

Figure 7-2: Change in Disaggregate Accessibility from No Build Scen to Unconstrained Scen

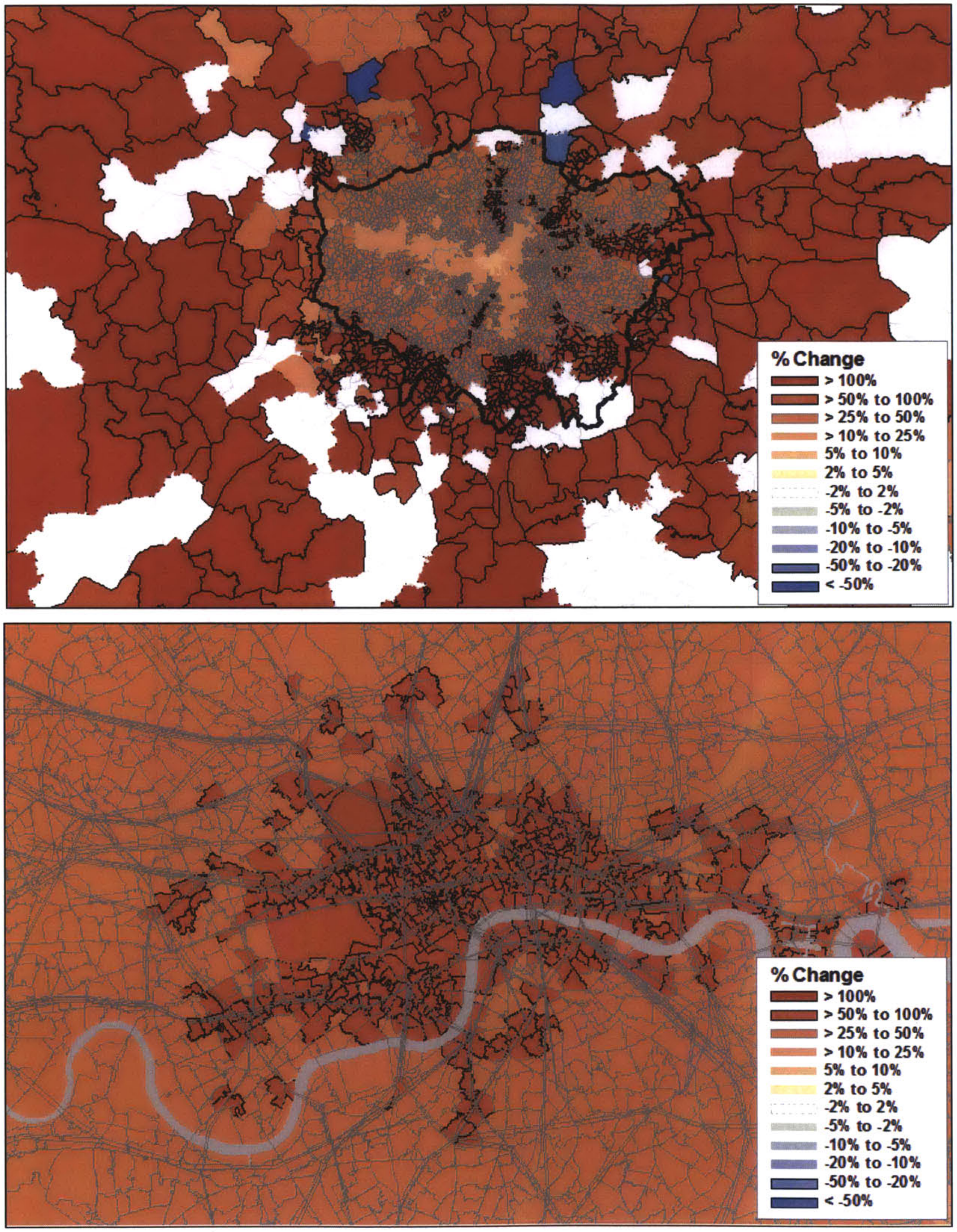


Table 7-3: Change in Aggregate Accessibility from No Build Scen to Unconstrained Scen

	Jobs	People	% Change Jobs	% Change People
Central London	1,674,417	2,191,268	13.6%	61.5%
Isle of Dogs	975,467	1,581,333	31.7%	55.3%
Inner London- Ring	921,252	1,414,439	28.1%	43.3%
Inner London-All	971,126	1,806,077	26.2%	53.9%
Outer London-Ring	478,847	752,967	37.3%	30.1%
London-All	673,007	1,375,852	30.8%	47.8%
Camden	1,249,670	2,035,064	22.9%	56.9%
City of London	1,867,898	2,363,541	10.9%	61.1%
Croydon	414,938	775,853	59.5%	34.1%
Ealing	595,571	923,136	24.7%	33.2%
Enfield	440,852	690,496	41.1%	25.2%
Greenwich	477,815	816,870	30.9%	32.1%
Hackney	993,314	1,574,404	20.7%	41.4%
Hammersmith	947,052	1,370,889	23.8%	43.9%
Harrow	480,769	780,477	27.1%	29.1%
Havering	383,762	616,562	47.9%	28.9%
Merton	563,901	982,535	39.3%	34.4%
Newham	748,885	1,148,585	46.9%	35.5%
Richmond	449,721	692,117	31.4%	29.2%
Southwark	1,023,102	1,646,659	18.3%	50.9%
Dacorum	206,120	281,192	177.7%	43.3%
Dartford	150,902	169,547	90.2%	24.2%
Epsom and Ewell	190,458	287,766	102.7%	28.7%
Slough	265,858	333,667	98.7%	32.3%
Watford	318,926	490,096	50.0%	35.8%
Welwyn Hatfield	309,698	438,012	112.9%	35.6%
Wycombe	43,155	24,588	392.7%	18.3%

Table 7-4: Change in Accessibility at Development Sites from No Build Scen to Unconstrained Scen

Development Site	Jobs	People	% Change Jobs	% Change People
Old Oak Common	437,181	548,454	14.1%	36.4%
Euston	1,999,877	2,486,619	26.0%	64.8%
Kings Cross	1,922,721	2,432,424	25.3%	57.5%
Stratford City	1,311,203	1,923,172	47.5%	39.1%
White City	667,544	795,580	16.2%	37.0%
The Royals	652,273	1,024,472	37.3%	49.1%
Canary Wharf	1,339,233	1,867,519	31.0%	57.9%
Silvertown Quay	785,342	1,202,390	51.8%	44.6%
Greenwich Peninsula	823,401	1,252,709	58.7%	59.8%
Ruskin Square	698,925	1,178,039	87.9%	44.5%
9 Elms	1,016,283	1,212,583	22.2%	43.7%
Earls Court	1,355,290	1,838,665	28.0%	56.7%
Chiswick Park	743,174	1,086,648	16.9%	33.0%
Waterloo	1,687,643	1,988,809	10.3%	56.3%
Paddington	1,683,811	2,259,437	13.2%	58.5%
Wembley	505,174	817,313	18.6%	26.1%

7.2 No Boarding Penalty

There could be an asymmetric spatial effect on accessibility from not including a boarding penalty in transit assignment, which would impact the (perceived) attractiveness of zones for development. For OD pairs where the preferred path requires users to board into a bottleneck, the loss in accessibility would tend to be understated. Furthermore, without a variable boarding penalty, it may not be possible to represent the vulnerability of these ODs: any growth in upstream demand would only make it that much harder to board and use the preferred path.

However, the accessibility loss to OD pairs where the preferred path does *not* require a boarding a crowded vehicle will tend to be *overstated*. Without a penalty, downstream users are no longer in a vulnerable position, and cannot simply be displaced by upstream users. If the V/C ratio is only controlled by a link-based discomfort effect, then this will affect upstream and downstream users the same, and cause some upstream users to needlessly switch paths.

7.2.1 Link Volumes

Figure 7-3 shows the change in network flow when no boarding penalty is applied. More demand is loaded onto a number of key routes such as VLSB and the NLBSB. Along these routes, there is a proportionally greater increase in demand after stops that involve difficult transfers, such as after Euston on VLSB and King's Cross on NLBSB.

V/C ratios are much higher when no boarding penalty is used (see Table 7-6). For example, on VLSB, nearly 30% of demand is at a volume to capacity over one.

Figure 7-3: Change in Network Flow from No Build Scen to NSP Scen

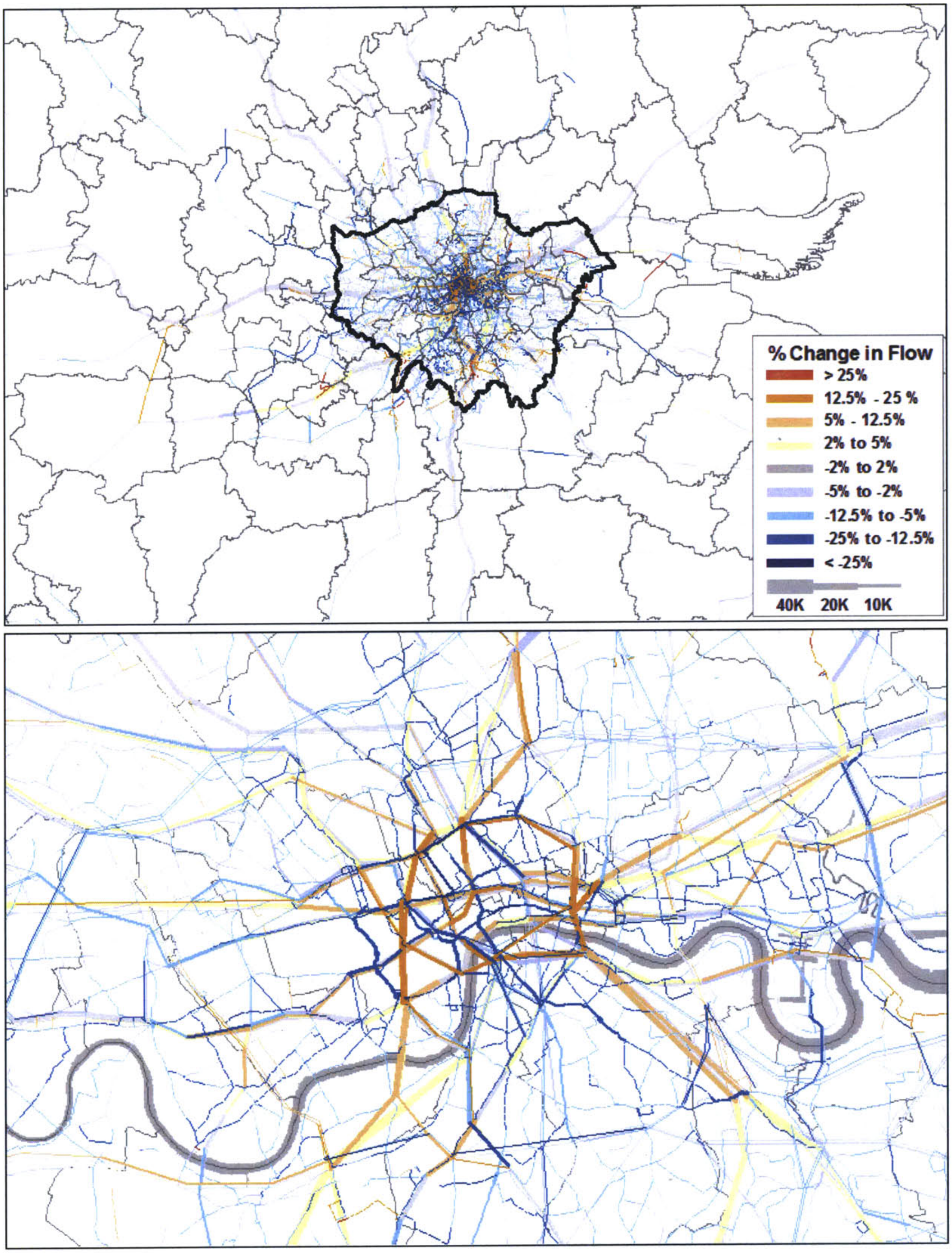


Table 7-5: V/C Ratio Distribution of Stops in NSP Scen

Line	Stops	% Stops below Volume/Capacity Ratio < .25	< .5	< .7	< .9	< 1	< 1.1
Lines Into Euston	251	41.8%	60.2%	71.3%	82.9%	92.8%	99.2%
Victoria SB	27	14.8%	37.0%	48.1%	59.3%	70.4%	85.2%
Northern Bank SB	89	20.2%	57.3%	64.0%	78.7%	96.6%	100.0%
Northern Charing SB	56	14.3%	32.1%	50.0%	75.0%	94.6%	100.0%
Piccadilly SB	266	27.8%	55.6%	69.2%	82.3%	90.6%	99.6%
Crossrail EAST	179	54.7%	67.0%	79.9%	93.3%	96.1%	99.4%
Hammersmith, Circle, Metropolitan EB	155	14.8%	36.8%	63.9%	98.7%	100.0%	100.0%
Other Underground	2779	35.0%	60.8%	78.8%	90.1%	95.7%	99.3%
DLR	159	17.0%	66.0%	93.7%	99.4%	100.0%	100.0%
Other Overground	282	16.7%	62.1%	84.0%	96.1%	98.9%	99.6%
Other TOC	8057	31.8%	57.8%	74.2%	86.9%	91.3%	94.5%

Table 7-6: Change in V/C Ratio Distribution of Stops from No Build Scen to NSP Scen

Line	Δ Stops	Δ % Stops below Volume/Capacity Ratio < .25	< .5	< .7	< .9	< 1	< 1.1
Lines Into Euston	0	0.4%	↑ 7.2%	↑ 4.0%	↓ -1.6%	↓ -1.6%	0.4%
Victoria SB	0	↓ -7.4%	↑ 3.7%	↓ -3.7%	↓ -3.7%	↓ -14.8%	↓ -14.8%
Northern Bank SB	0	↑ 2.2%	↑ 3.4%	↓ -1.1%	↓ -12.4%	↓ -3.4%	0.0%
Northern Charing SB	0	↑ 1.8%	↑ 1.8%	↑ 1.8%	↓ -10.7%	↓ -5.4%	0.0%
Piccadilly SB	0	0.0%	-0.8%	↓ -4.1%	-0.8%	↓ -4.1%	-0.4%
Crossrail EAST	0	↑ 2.8%	0.0%	0.0%	-0.6%	↓ -1.7%	0.0%
Hammersmith, Circle,	0	↑ 1.9%	↓ -1.9%	0.6%	↓ -1.3%	0.0%	0.0%
Other Underground	0	0.4%	0.7%	-0.1%	↓ -2.7%	↓ -3.7%	-0.7%
DLR	0	↑ 3.8%	-0.6%	↑ 5.0%	-0.6%	0.0%	0.0%
Other Overground	0	0.4%	↑ 6.4%	↑ 1.1%	↓ -2.1%	↓ -1.1%	-0.4%
Other TOC	0	0.5%	↑ 1.1%	0.8%	-0.1%	-0.6%	-0.8%

7.2.2 Accessibility

As discussed in the introduction to this section, omitting a boarding penalty could place an upward bias on the accessibility levels of ODs that involve difficult transfers. This bias might cause analysts to conclude that certain origins and destinations are more attractive to businesses and households than is realistic.

Figure 7-4 shows the disaggregate change in accessibility when no boarding penalty is applied. Although most of the zones show a higher level of accessibility, which can be partially attributed to the fact that only a modest link-based penalty is being used to suppress V/C ratios (see Figure 6-1), some zones show a disproportionately large increase in accessibility, suggesting that they were adversely impacted from transfers in the No Build scenario.

A number of origins in the Commuter Ring appear to be strongly impacted by the omission of boarding penalties. Within London, origins along the Piccadilly Line SB (PLSB), VLSB, and Northern Line northbound corridors, are impacted the most.

Destinations along VLSB after the transfer at Euston, and destinations along NLBSB, after the transfer at King's Cross, are disproportionately impacted by the omission of the boarding penalty. This result underscores how failing to represent the difficultly of transfers at key stations in London, such as at Euston, could distort accessibility levels well away from the actual transfer point.

Table 7-7 shows that the omission of a boarding penalty impacts districts in the Commuter Ring the most, with Dacorum experiencing the largest change. Within London, Croydon is affected the most at the origin end, and the Isle of Dogs is affected the most at the destination end. Among the development sites, the biggest change in access to jobs occurs in the Greenwich peninsula and Ruskin square sites (see Table 7-8). The Greenwich peninsula site is at especially precarious position as residents and business would have a limited ability to withstand a deterioration in Jubilee Line service.

Figure 7-4: Change in Disaggregate Accessibility from No Build Scen to NSP Scen

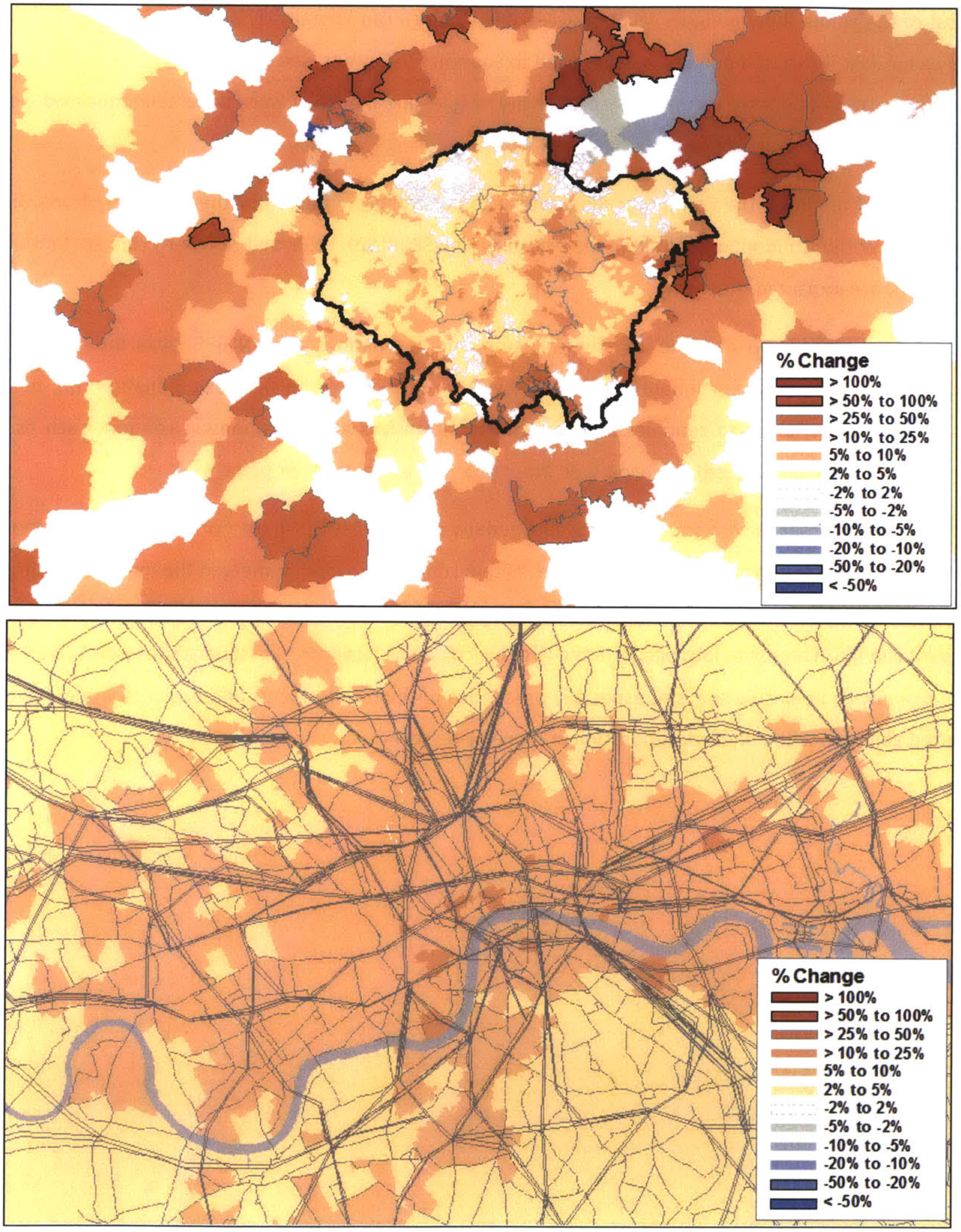


Table 7-7: Change in Aggregate Accessibility from No Build Scen to NSP Scen

	Jobs	People	% Change Jobs	% Change People
Central London	1,533,026	1,466,159	4.0%	8.0%
Isle of Dogs	808,604	1,102,757	9.2%	8.3%
Inner London- Ring	765,526	1,042,832	6.4%	5.7%
Inner London-All	816,350	1,256,252	6.1%	7.0%
Outer London-Ring	364,620	603,303	4.5%	4.2%
London-All	542,787	989,504	5.5%	6.3%
Camden	1,071,900	1,392,488	5.5%	7.4%
City of London	1,737,536	1,585,519	3.2%	8.1%
Croydon	285,899	602,988	9.9%	4.2%
Ealing	498,553	725,924	4.4%	4.7%
Enfield	326,937	570,936	4.7%	3.5%
Greenwich	387,072	644,631	6.0%	4.3%
Hackney	862,941	1,171,678	4.9%	5.2%
Hammersmith	806,661	1,006,358	5.4%	5.7%
Harrow	391,894	631,559	3.6%	4.4%
Havering	267,550	501,773	3.1%	4.9%
Merton	416,560	764,877	2.9%	4.6%
Newham	557,627	889,778	9.4%	5.0%
Richmond	358,301	556,634	4.7%	3.9%
Southwark	908,794	1,161,892	5.1%	6.5%
Dacorum	102,305	212,531	37.8%	8.3%
Dartford	90,242	142,431	13.8%	4.4%
Epsom and Ewell	104,375	231,828	11.1%	3.6%
Slough	154,044	264,592	15.1%	4.9%
Watford	236,963	380,716	11.4%	5.5%
Welwyn Hatfield	165,650	340,930	13.9%	5.6%
Wycombe	9,160	22,180	4.6%	6.8%

Table 7-8: Change in Accessibility at Development Sites from No Build Scen to NSP Scen

Development Site	Jobs	People	% Change Jobs	% Change People
Old Oak Common	394,221	423,112	2.9%	5.3%
Euston	1,694,899	1,613,426	6.8%	6.9%
Kings Cross	1,646,310	1,641,997	7.3%	6.3%
Stratford City	979,808	1,454,094	10.2%	5.2%
White City	591,875	608,350	3.1%	4.7%
The Royals	514,267	734,504	8.3%	6.9%
Canary Wharf	1,109,998	1,285,459	8.6%	8.7%
Silvertown Quay	574,147	880,198	11.0%	5.8%
Greenwich Peninsula	613,305	857,667	18.2%	9.4%
Ruskin Square	430,248	853,512	15.7%	4.7%
9 Elms	888,073	888,873	6.8%	5.3%
Earls Court	1,141,787	1,262,945	7.8%	7.6%
Chiswick Park	653,253	855,778	2.8%	4.7%
Waterloo	1,576,817	1,359,587	3.1%	6.9%
Paddington	1,519,278	1,533,611	2.1%	7.6%
Wembley	437,398	669,787	2.7%	3.3%

8 CAPACITY CONSTRAINTS IN HS2 SCENARIOS

One of the stated purposes of the HS2 project is to add new north-south capacity, thereby relaxing capacity constraints on the WCML. The released WCML capacity could then be used for a number of purposes such as improving commuter service into London or increasing freight traffic.

This thesis considers capacity from the perspective of vehicle crowding and maximum passenger throughput. While the HS2 project is expected to reduce vehicle crowding levels, increasing the maximum number of possible trains per hour into London can simultaneously yield other accessibility benefits. In particular, adding new train paths and reducing large headways could improve the level of regional and inter-regional accessibility in Great Britain even for markets where crowding is not a factor.

Improving inter-regional access, especially for cities in northern Great Britain, is the primary argument for HS2. However, the analysis in this chapter is restricted to examining HS2's impact on travel within the southeast of England, and does not consider inter-regional accessibility benefits. For London, the released capacity would present an opportunity to improve access to commuter markets. Complementary HS2 investments, such as the West Coast Main Line extension, could further enhance access to central London.

The analysis in this chapter reflects new routes and train frequencies in the southeast of England, and a new demand matrix (see Table 5-1) that includes roughly 15,000 more peak hour trips in the region.

The first section looks at the basic HS2 investment as coded by TfL staff in the Railplan model. The second section looks at two proposed complementary HS2 investments, the proposed extension of the WCML to Crossrail and a new Overground station at Old Oak Common.

8.1 HS2

The HS2 project would increase the maximum vehicle and passenger flow into London. Even if only a modest amount of new travel is induced from HS2, the increase in vehicle flow could improve connections to commuter markets, strengthen freight paths, or reduce crowding levels.

However, there could be a complicated relationship between HS2 and crowding levels within London's public transport system. Most arriving HS2 passengers would not complete their trip at either Euston or Old Oak Common and would need to transfer to another mode. While some HS2 business travelers may use a taxi to complete their journeys, London's public transport system is assumed to be the preferred mode for most. On one hand, crowding in the public transport system, such as along VLSB and NLSB, could push HS2 passengers away from these routes and decrease the value of the project. Therefore, reducing crowding along these routes would directly benefit the HS2 project. On the other hand, the HS2 project could itself exacerbate crowding within the public transport system, and reduce the net benefit of the project, considering the external costs to TfL.

Some of the concerns for overloading in VLSB and NLSB were partially addressed when the UK Government agreed to build an underground walk connection between Euston Station and Euston Square Station, which serves the Hammersmith & City, Circle, and Metropolitan lines and provides an alternative path to the City of London.

Modeling the difficultly of the remaining transfers to VLSB and NLSB cannot easily be done with an assignment model that has invariant boarding penalties or only applies a link-based penalty. Section 7.2.1 showed that removing the variable boarding penalties disproportionality increases demand on links that immediately follow bottlenecks. This result suggests that the omission of a variable boarding penalty in transit assignment may lead to an over-prediction of how many HS2 passengers would transfer at Euston.

Simulation models may be the most appropriate for representing the true distribution of wait times for people boarding crowded vehicles such as VLSB, but small-scale simulation models, may treat passenger arrival rates as an exogenous variables. In reality, some HS2 passengers would pick a different path or travel earlier in the day if crowding within Euston became too severe. To be effective, the model would have to include a route choice component. However, this thesis does not consider the use of a dynamic model in long-range modeling.

A static assignment model with boarding penalties, such as the one used in this analysis, can capture some of crowding effects relevant to HS2, but it is just a starting solution. For example, the models cannot explicitly represent vehicle queuing and the boarding penalty is based on an abstract relationship between average crowding and average capacity. Furthermore, a large threat to economic value of the project would be an actual loss in line capacity from excessive dwell times, but this was not immediately possible to simulate in the current model.

Finally, crowding problems are not restricted to vehicles. There could be crowding within Euston station itself, as passengers compete for standing space and escalator use. This type of effect was not modeled in this chapter, but it needs to be reviewed.

8.1.1 Link Volumes and Capacity Analysis

Figure 8-1 shows the change in link flows with the introduction of HS2. A comparison is presented only for links that existed in both the No Build and HS2 scenarios. For example, no change in volumes is reported for the HS2 infrastructure itself or for the realigned Crossrail path between Acton Main Line and Paddington.

Flows into central London along the principal commuter rail lines, such as the WCML and ECML, are substantially reduced with HS2. Among WCML paths heading to Euston, there is a 15 percentage point reduction in the number of links with a V/C ratio higher than .8, and about a 6 percentage point reduction in the number of links with a V/C ratio higher than .9 (see Table 8-2).

Taken at face value, the HS2 scenario did not generate a significant number of new boarders for VLSB or NLSB. The improved walk from Euston to Euston Square helps shift some of the new demand to the Hammersmith and City line, as about 1,000 more passengers travel eastbound from Euston Square in the HS2 scenario.

However, an important reason to explain why the model predicts a manageable level of transfers to VLSB and NLSB is that the V/C ratio is already quite high and passengers seek alternative paths through the system. In reality, some of these passengers could attempt to force their way onto trains. In any case, whether HS2 passengers need to seek alternative paths or force their way onto trains, the lack of available capacity on VLSB and NLSB could be suppressing the value of the HS2 investment.

The HS2 investment might not be substantially disruptive to London's public transport along VLSB and NLSB. Part of this is due to the fact that the HS2 passengers are in a precarious position where they have to internalize the crowding problem and adjust their own travel behavior, and cannot pass any disbenefits on to other users in the system. If this analysis had been done using an assignment algorithm that relies entirely on link-based discomfort penalties, then HS2 passengers could have externalized the crowding disbenefits, even illogically displacing upstream passengers

Figure 8-1: Change in Network Flow from No Build Scen to HS2 Scen

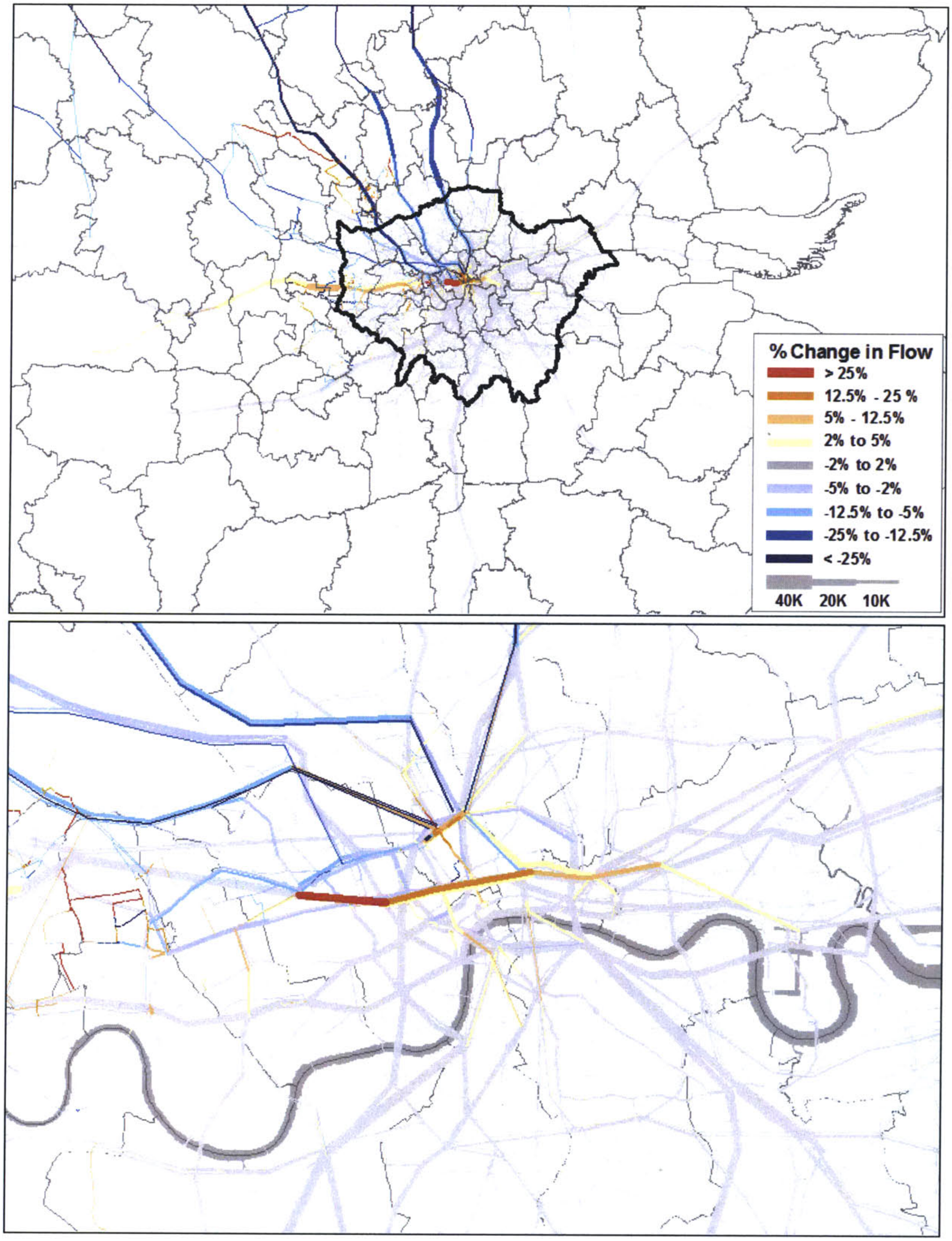


Table 8-1: V/C Ratio Distribution of Stops in HS2 Scen

Line	Stops	% Stops below Volume/Capacity Ratio <.25	<.5	<.7	<.9	<1	<1.1
Lines Into Euston	118	54.2%	68.6%	88.1%	100.0%	100.0%	100.0%
Victoria SB	27	22.2%	33.3%	48.1%	63.0%	85.2%	100.0%
Northern Bank SB	89	18.0%	53.9%	64.0%	89.9%	100.0%	100.0%
Northern Charing SB	56	12.5%	30.4%	48.2%	85.7%	100.0%	100.0%
Piccadilly SB	266	27.8%	56.4%	73.3%	84.2%	95.1%	100.0%
Crossrail EAST	169	50.3%	59.2%	80.5%	98.2%	99.4%	100.0%
Hammersmith, Circle, Metropolitan EB	155	13.5%	38.1%	64.5%	99.4%	100.0%	100.0%
Other Underground	2766	35.4%	60.3%	79.3%	92.8%	99.4%	100.0%
DLR	159	13.2%	66.7%	88.7%	100.0%	100.0%	100.0%
Other Overground	282	16.0%	55.7%	83.0%	98.2%	100.0%	100.0%
Other TOC	8036	31.3%	57.2%	73.7%	87.1%	92.1%	95.3%
HS2	4	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 8-2: Change in V/C Ratio Distribution of Stops from No Build Scen to HS2 Scen

Line	Δ Stops	Δ % Stops below Volume/Capacity Ratio <.25	<.5	<.7	<.9	<1	<1.1
Lines Into Euston	-133	↑ 12.8%	↑ 15.7%	↑ 20.8%	↑ 15.5%	↑ 5.6%	↑ 1.2%
Victoria SB	0	0.0%	0.0%	↓ -3.7%	0.0%	0.0%	0.0%
Northern Bank SB	0	0.0%	0.0%	↓ -1.1%	↓ -1.1%	0.0%	0.0%
Northern Charing SB	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Piccadilly SB	0	0.0%	0.0%	0.0%	↑ 1.1%	0.4%	0.0%
Crossrail EAST	-10	↓ -1.7%	↓ -7.9%	0.6%	↑ 4.4%	↑ 1.6%	0.6%
Hammersmith, Circle, Me	0	0.6%	-0.6%	↑ 1.3%	-0.6%	0.0%	0.0%
Other Underground	-13	0.7%	0.2%	0.4%	0.0%	0.0%	0.0%
DLR	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Other Overground	0	-0.4%	0.0%	0.0%	0.0%	0.0%	0.0%
Other TOC	-21	0.1%	0.4%	0.2%	0.2%	0.2%	0.0%

Table 8-3: User Movements near Euston and Euston Square Station in HS2 Scen

Entering Station	Leaving Station: Victoria SB	NL Bank SB	NL Charing SB	MCC EB East	All	VoC
HS2	550	258	892	2,126	9,127	0.46
WCML	532	2,066	718	3,716	14,141	0.63
Victoria SB	24,550	21	0	0	25,830	0.98
NL Bank SB	538	7,640	0	0	16,230	0.85
NL Charing SB	0	0	16,071	3	16,350	0.86
MCC EB East	0	0	0	19,495	20,637	0.72
All	25,990	17,457	17,234	22,798		
VoC	0.99	0.92	0.91	0.80		

NL = Northern Line; MCC = Metropolitan, City, Hammersmith; VoC = Volume to Capacity

Table 8-4: Change in User Movements near Euston and Euston Square from No Build Scen to HS2 Scen

Entering Station	Leaving Station: Victoria SB	NL Bank SB	NL Charing SB	MCC EB East**	All	Δ VoC
WCML + HS2*	121	-17	176		7,130	-
WCML	-429	-275	-716	-	-1,997	-0.06
Victoria SB	-182	4	0	-	5	0.00
NL Bank SB	10	-62	0	-	-19	0.00
NL Charing SB	0	0	-70	-	19	0.00
MCC EB East	-	-	-	-	-282	-0.01
All	-17	-156	43	1,102		
Δ VoC	0.00	-0.01	0.00	0.04		

NL = Northern Line; MCC = Metropolitan, City, Hammersmith; VoC = Volume to Capacity

* Compares totals from WCML + HS2 agasint WCML in No Build

** Does not have a direct transfer to HS2 in No Build

8.1.2 Accessibility

The primary accessibility benefit of the HS2 project is for inter-regional markets, such as London and Birmingham, and London and Manchester. This section does not examine the inter-regional accessibility benefits, but considers the accessibility benefits within London's commuter market.

With the available WCML capacity, resources could be used to better integrate underserved market pairs in the southeast. However, this type of path optimization problem is not performed in this chapter, and the new service assumptions are left as coded by TfL staff.

The HS2 project improves access to jobs for households to the northwest of London, particularly in Hertfordshire, that benefit from reduced vehicle crowding and new stops (see Figure 8-2). The accessibility impact is significant in a number of cases, with the weighted value increasing by over 50%. In Dacorum, the aggregate change in access to jobs is over 55% (see Table 8-5).

Access from households to central London is slightly improved with HS2. The accessibility level at land uses near Euston increases by over 5%, which does not even reflect the improved access to central and northern Great Britain.

Although the Old Oak Common site shows a dramatic improvement in access to jobs and access from households to the site (see Table 8-6), much of this change is due to the addition of a Crossrail station that provides direct access to central London. The new accessibility level of Old Oak Common is on par with Canary Wharf, even before factoring in the inter-regional benefits. The Crossrail station might make the Old Oak Common site competitive for (at least) residential development even without HS2.

Figure 8-2: Percent change in Accessibility from No Build to HS2

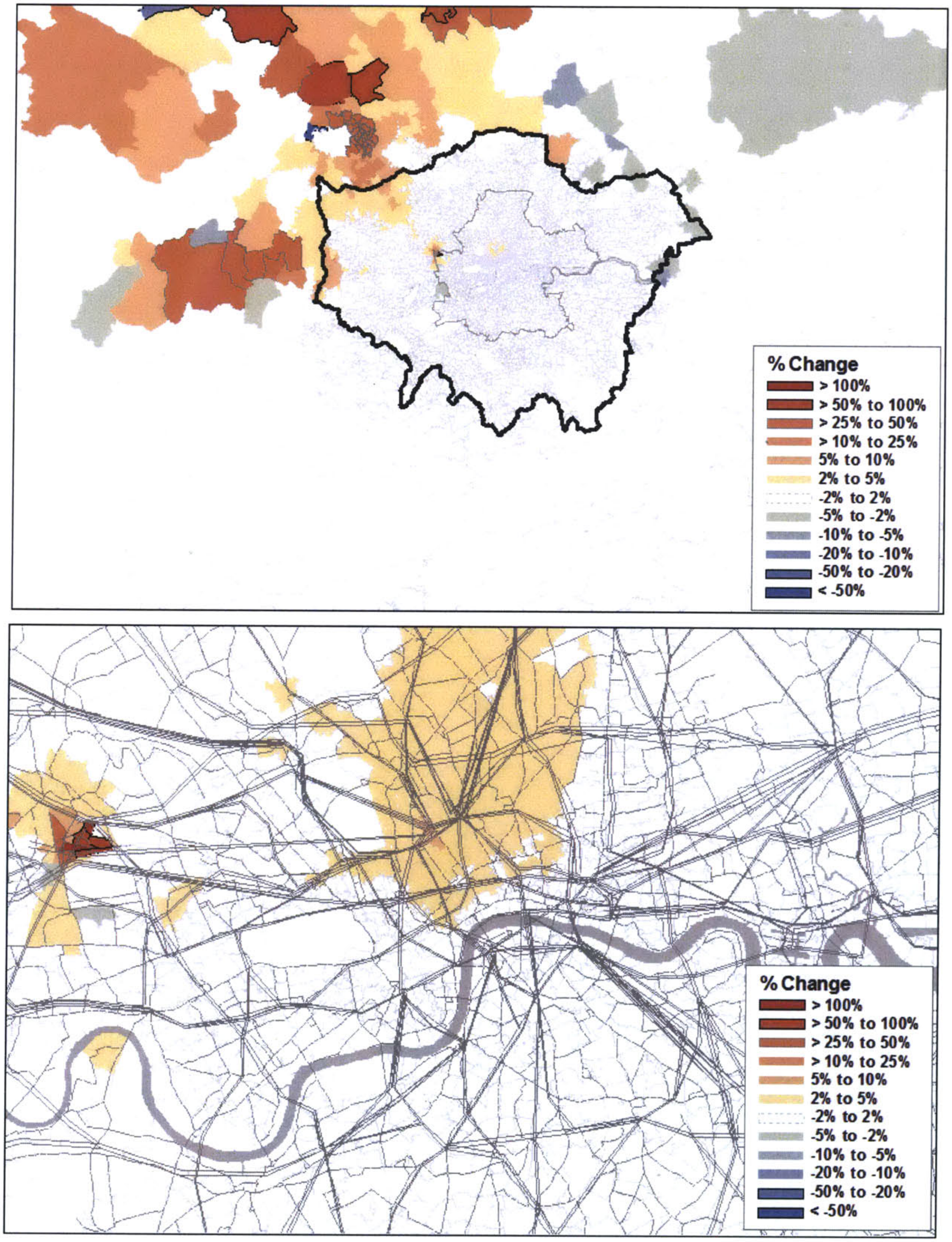


Table 8-5: Aggregate Change in Accessibility from No Build to HS2

	Jobs	People	% Change Jobs	% Change People
Central London	1,489,843	1,380,172	1.1%	1.7%
Isle of Dogs	740,007	1,019,155	-0.1%	0.1%
Inner London- Ring	722,509	996,196	0.4%	0.9%
Inner London-All	773,322	1,189,777	0.5%	1.4%
Outer London-Ring	350,629	582,132	0.5%	0.6%
London-All	517,343	941,537	0.5%	1.2%
Camden	1,031,176	1,329,082	1.5%	2.5%
City of London	1,701,162	1,490,662	1.0%	1.6%
Croydon	259,382	579,173	-0.3%	0.1%
Ealing	483,563	698,044	1.3%	0.7%
Enfield	313,226	555,529	0.3%	0.7%
Greenwich	364,461	618,309	-0.2%	0.0%
Hackney	827,552	1,128,581	0.6%	1.4%
Hammersmith	770,552	963,431	0.7%	1.2%
Harrow	388,725	617,552	2.8%	2.1%
Havering	258,110	478,873	-0.5%	0.1%
Merton	404,258	731,710	-0.2%	0.1%
Newham	508,630	850,356	-0.2%	0.3%
Richmond	340,792	536,876	-0.4%	0.2%
Southwark	866,702	1,098,673	0.2%	0.7%
Dacorum	115,691	225,922	55.9%	15.1%
Dartford	78,925	136,261	-0.5%	-0.1%
Epsom and Ewell	93,615	223,503	-0.3%	-0.1%
Slough	164,258	271,734	22.8%	7.7%
Watford	252,111	418,922	18.5%	16.1%
Welwyn Hatfield	153,345	328,809	5.4%	1.8%
Wycombe	9,010	22,176	2.9%	6.7%

Table 8-6: Change in Accessibility at Development Sites form No Build to HS2

Development Site	Jobs	People	% Change Jobs	% Change People
Old Oak Common	958,357	1,056,625	↑ 150.1%	↑ 162.9%
Euston	1,663,173	1,595,241	↑ 4.8%	↑ 5.7%
Kings Cross	1,564,253	1,584,552	↑ 1.9%	↑ 2.6%
Stratford City	888,812	1,393,214	0.0%	0.8%
White City	598,277	583,006	↑ 4.2%	0.4%
The Royals	473,699	687,224	-0.3%	0.0%
Canary Wharf	1,023,628	1,184,820	0.2%	0.2%
Silvertown Quay	518,566	834,150	0.3%	0.3%
Greenwich Peninsula	517,415	784,863	-0.3%	0.1%
Ruskin Square	370,519	816,620	-0.4%	0.2%
9 Elms	833,636	844,591	0.2%	0.1%
Earls Court	1,064,502	1,183,526	0.5%	0.9%
Chiswick Park	636,362	823,974	0.1%	0.9%
Waterloo	1,539,285	1,289,962	0.6%	↑ 1.4%
Paddington	1,459,095	1,446,030	↓ -1.9%	↑ 1.4%
Wembley	432,933	655,818	↑ 1.6%	↑ 1.2%

8.1.3 Select Link

The released WCML capacity from the HS2 investment is expected to reduce crowding levels and substantially improve the travel experience for certain districts in the southeast of England. For trips going to central London, the model results suggest that there may be a 2 percentage point change in the amount of time at a volume to capacity ratio above .8, and also a 2 percentage point change in the number of trips that traverse a bottleneck (see Table 8-7).

Demand coming from a number of origins, especially in the Commuter Ring, is expected to spend less time at very high levels of crowding, and there is generally a reduction in the number of trips that pass through a bottleneck. The origin district that benefits the most is Dacorum, which witnesses nearly a 60 percentage point reduction in the number of trips going through a bottleneck, and nearly a 40 percentage point reduction in the number of trips that need to board into a bottleneck. Delivery of the HS2 project could be important for ensuring that commuter districts such as Dacorum realize the forecasted, unconstrained growth.

Table 8-7: Change in Select Link V/C Ratio Distribution from No Build to HS2

	Δ % TIME AT VOLUME/CAPACITY RATIO						Δ % Thr Bottle	Δ % Brd Bottle
DESTINATIONS	**<.25**	**<.5**	**<.7**	**<.9**	**<1**	**<1.1**	**Perc**	**Perc**
City of London	-0.5%	3.0%	2.8%	1.9%	1.3%	0.3%	-2.5%	-0.6%
Central London	-0.5%	2.8%	2.7%	1.9%	1.3%	0.3%	-2.3%	-0.6%
Isle of Dogs	-0.3%	0.6%	1.9%	1.2%	0.9%	0.4%	-3.5%	-0.5%
Inner London- Ring	-0.6%	1.5%	1.5%	0.9%	0.7%	0.2%	-1.2%	-0.3%
Inner London-All	-0.6%	2.2%	2.2%	1.5%	1.1%	0.3%	-1.8%	-0.5%
Outer London-Ring	-0.4%	0.5%	0.5%	0.3%	0.2%	0.0%	-0.4%	-0.1%
London-All	-0.6%	1.8%	1.8%	1.2%	0.9%	0.2%	-1.5%	-0.4%
ORIGINS	**<.25**	**<.5**	**<.7**	**<.9**	**<1**	**<1.1**	**Perc**	**Perc**
Inner London	-1.3%	1.0%	0.2%	0.1%	-0.1%	0.0%	0.1%	0.2%
Outer Ring	-1.1%	0.7%	0.3%	0.2%	0.0%	0.0%	-1.4%	0.0%
Commuter Ring	0.0%	0.3%	1.3%	1.6%	0.8%	0.2%	-2.6%	-1.5%
Camden	-2.8%	2.6%	0.8%	-0.3%	-0.1%	0.0%	0.8%	0.1%
Croydon	-1.0%	0.1%	0.2%	0.3%	0.2%	0.0%	0.2%	-0.1%
Ealing	-1.4%	-0.2%	0.5%	1.6%	0.3%	0.0%	-10.0%	0.0%
Enfield	-1.0%	0.9%	0.3%	-0.3%	0.1%	0.0%	-0.2%	0.0%
Greenwich	-0.5%	0.0%	-0.3%	0.0%	0.0%	0.0%	0.0%	0.0%
Hackney	-1.1%	0.3%	-0.1%	0.1%	0.0%	0.0%	0.1%	0.3%
Hammersmith	-1.0%	1.1%	0.3%	-0.2%	-0.3%	0.0%	-0.2%	0.3%
Harrow	0.0%	1.8%	0.3%	-0.3%	-0.2%	0.0%	-0.1%	0.0%
Havering	-0.7%	0.0%	-1.0%	0.1%	0.0%	0.0%	0.0%	0.0%
Merton	-1.2%	0.9%	0.4%	0.2%	0.1%	0.0%	0.3%	0.1%
Newham	-0.3%	0.0%	-0.7%	0.1%	-0.1%	0.0%	-0.2%	0.7%
Richmond	-2.3%	1.9%	1.3%	0.0%	0.1%	0.0%	-0.3%	0.0%
Southwark	-1.2%	0.6%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%
Dacorum	-0.4%	-3.1%	7.9%	18.6%	7.0%	2.4%	-58.1%	-37.5%
Dartford	-0.3%	0.2%	-0.3%	-0.1%	-0.2%	0.0%	-0.6%	0.1%
Epsom and Ewell	-0.2%	0.0%	0.1%	-0.1%	0.0%	0.0%	0.1%	0.0%
Slough	-4.2%	-2.4%	2.2%	12.1%	3.5%	1.1%	1.7%	-6.0%
Watford	-2.8%	0.4%	-2.7%	3.1%	0.4%	0.0%	-16.6%	-0.4%
Welwyn Hatfield	-1.0%	-0.5%	0.6%	5.2%	7.0%	0.0%	-0.7%	-0.5%
Wycombe	3.9%	-1.8%	-1.1%	-1.1%	-0.4%	-0.8%	-1.5%	-10.8%

Thr = through; Brd = Board; Bottle = Bottleneck

8.1.4 Cordon Capacity

The HS2 add over 20,000 new peak hour seats into central London. This increase can help sustain growth within London and ensure that there is sufficient capacity for inter-regional trips.

Table 8-8 shows the change in cordon capacity with HS2 and other related schemes, such as modifying the Crossrail path to serve Old Oak Common. There is an appreciable increase in the supply of public transport service into central London and over a two percentage point reduction in the cordon V/C ratio.

Table 8-8 also highlights some of the weaknesses of the cordon capacity approach. The recorded changes in demand and supply are very sensitive to where the boundaries are drawn. A modification to Crossrail service affecting routes near the edge of the boundaries led to a large increase in the reported supply of capacity to central London even though the number of Crossrail trains per hour does not change for most stations in central London. The Hammersmith and Fulham district is shown to have over a 100,000 person increase in public transport capacity from adding a single Crossrail station near Old Oak Common. However, this increase in supply is partially offset by an increase in demand into the district.

Table 8-8: Change in Cordon Capacity from No Build to HS2

	All Trains			Trains Excluding TOCs		
	Δ Demand	Δ Supply	Δ % VoC	Δ Demand	Δ Supply	Δ % VoC
Central London	8,651	39,218	-1.9%	10,997	21,004	-0.7%
Inner London	4,692	21,215	-0.9%	-128	3,001	-0.4%
London	4,075	21,215	-2.3%	367	3,001	-1.0%
Isle of Dogs	624	0	0.5%	557	0	0.7%
Camden	3,816	19,073	-1.4%	-1,347	0	-0.3%
City of London	3,985	0	0.8%	3,648	0	1.3%
Croydon	194	0	0.2%	4	0	0.1%
Ealing	1,720	6,001	-0.2%	1,261	6,001	-0.6%
Enfield	-317	0	-0.5%	5	0	0.0%
Greenwich	208	0	0.1%	118	0	0.2%
Hackney	-16	0	0.0%	-45	0	-0.1%
Hammersmith	54,121	111,102	0.7%	21,675	54,010	-1.3%
Harrow	-3,266	-1,568	-2.7%	-1,211	0	-1.3%
Havering	58	0	0.1%	23	0	0.0%
Merton	-43	0	0.0%	7	0	0.0%
Newham	490	0	0.2%	419	0	0.2%
Richmond	-110	0	-0.2%	-5	0	0.0%
Southwark	1,292	0	0.3%	699	0	0.5%
Sutton	17	0	0.0%	0	0	-
Tower Hamlets	1,348	0	0.4%	1,306	0	0.5%
Waltham Forest	71	0	0.1%	72	0	0.1%
Westminster	4,464	21,004	-1.7%	11,883	21,004	-0.6%
Dacorum	-1,483	-348	-15.5%	854	0	-
Dartford	28	0	0.1%	0	0	-
Epsom and Ewell	19	0	0.1%	0	0	-
Slough	474	6,001	-5.3%	562	6,001	-5.9%
Watford	658	4,253	-3.2%	-240	0	-2.2%
Welwyn Hatfield	-472	0	-2.4%	0	0	-
Wycombe	-270	0	-4.0%	0	0	-

8.2 WCML Extension and Overground Station

This section examines the impact of two proposed complementary investments to HS2: the WCML Extension and the proposed Overground Station at Old Oak Common. The investments are evaluated together, and not independently, as the available Railplan network had both projects coded in the same scenario.

The WCML Extension can provide both long-term benefits to the southeast of England and short-term relief to Euston, depending on the project's completion date. If the WCML were completed before the opening of HS2, then there would be fewer vehicles and people moving through Euston during a difficult construction period. This could help reduce the risk of construction challenges causing HS2 project delays or WCML service disruptions.

In the long-run, the WCML extension could improve access to central London particularly from Hertforshire. If the WCML extension is completed sooner, then potential problems with difficult transfers to VLSB and NLSB could be mitigated at an earlier date. Addressing these transfers sooner, could eliminate a potential constraint on growth for districts near Hertfordshire.

The Overground station at Old Oak Common could improve both accessibility and capacity to the Old Oak Common development site, as well as provide a secondary means of access in the event of Crossrail disruptions. The Overground station and supporting infrastructure also slightly improves the overall north to south connectivity in London.

8.2.1 Link Volumes and Capacity Analysis

Flows into Euston are significantly reduced with the WCML extension as over 4000 fewer people arrive during the peak hour (see Table 8-11). However, there is only a small reduction in vehicle crowding. The percentage of links with a V/C ratio over .7 decreases by 3 points (see Table 8-10).

The WCML extension leads to only a modest 100 person reduction in the number of transfers between the WCML and VLSB, but an appreciable 600 person reduction in transfers to NLBSB. The small reduction in VLSB transfer is partly due to the fact that crowding conditions are already suppressing travelers from making transfer even before the WCML extension. In reality, if crowding on VLSB was never addressed, then there could be suppressed demand from Hertfordshire and other origins that would need to make a transfer at the station. The reduction in transfers to NLBSB leads to an appreciable 2 point improvement in the volume to capacity ratio.

However, the WCML extension does eventually exacerbate crowding on Crossrail EB, as flow increases by over 5% along some Crossrail links and there is almost a 2 percentage point decrease in the number of links with a volume to capacity ratio under .9. This result suggests that some of the crowding benefits from reduced flow into Euston would be partially offset by new crowding challenges on Crossrail EB unless further investment in increased capacity, such as Crossrail II, is made in timely fashion.

The Overground station draws demand onto the Overground routes heading towards Old Oak common and reduces flows along paths heading from south to north across the Thames. However, the addition of the Overground station introduces some crowding disbenefits as there is a 2 percentage point reduction in the number of stops with a volume to capacity ratio below .9 (see Table 8-10).

Figure 8-3: Change in Volume/Capacity ratio of stops from HS2 scen to WCML Ext scen

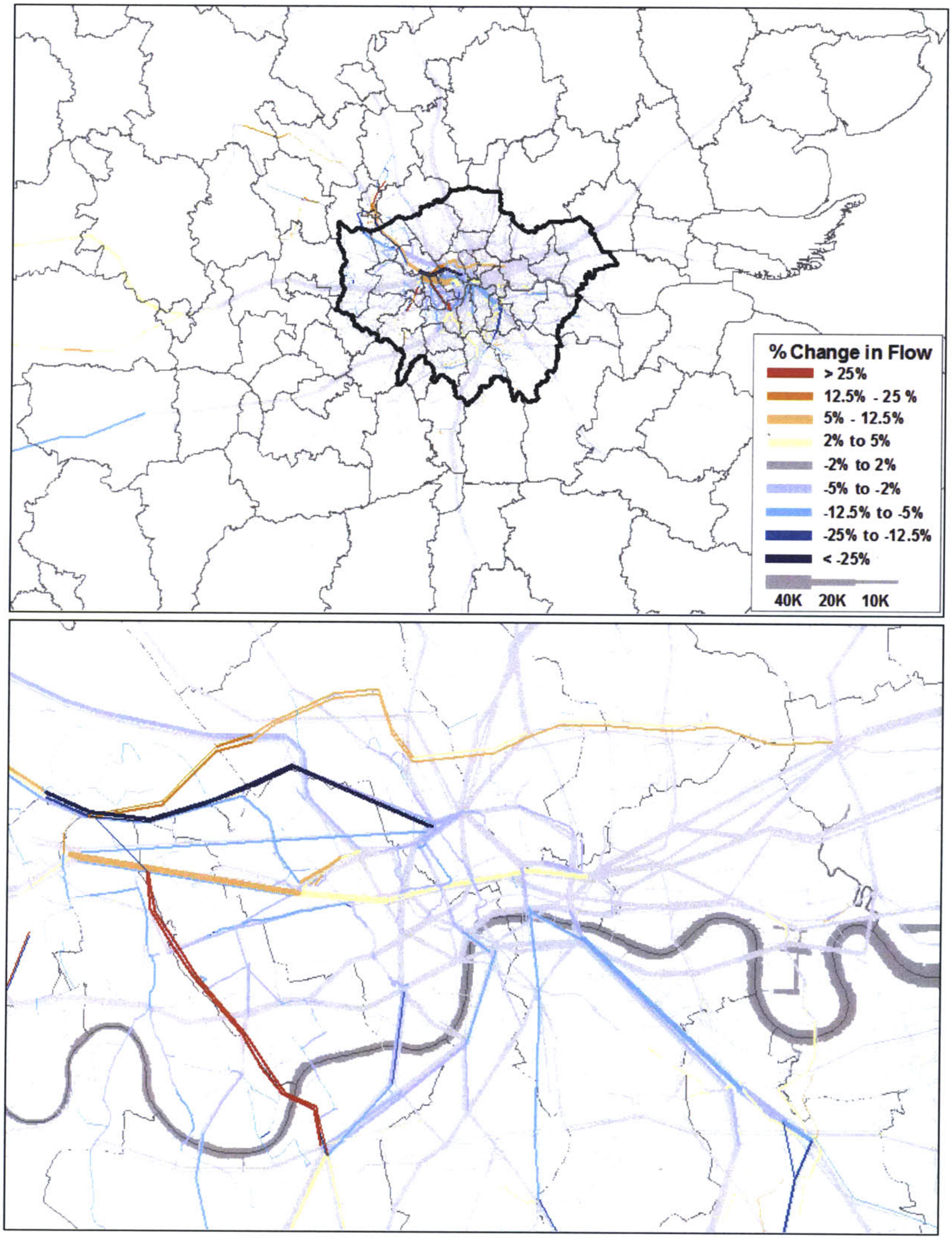


Table 8-9: V/C ratio of stops in WCML Ext scenario

Line	Stops	% Stops below Volume/Capacity Ratio					
		<.25	<.5	<.7	<.9	<1	<1.1
Lines Into Euston	100	54.0%	72.0%	91.0%	100.0%	100.0%	100.0%
Victoria SB	27	22.2%	33.3%	51.9%	63.0%	88.9%	100.0%
Northern Bank SB	89	18.0%	52.8%	64.0%	92.1%	100.0%	100.0%
Northern Charing SB	56	12.5%	32.1%	50.0%	85.7%	100.0%	100.0%
Piccadilly SB	266	27.8%	56.8%	73.3%	84.6%	95.1%	100.0%
Crossrail EAST	222	48.6%	62.2%	82.0%	96.4%	99.5%	100.0%
Hammersmith, Circle, Metropolitan EB	155	14.8%	38.7%	67.7%	100.0%	100.0%	100.0%
Other Underground	2819	35.7%	60.4%	79.1%	92.7%	99.4%	100.0%
DLR	159	13.8%	64.8%	88.1%	100.0%	100.0%	100.0%
Other Overground	296	17.9%	58.4%	83.8%	95.9%	99.7%	100.0%
Other TOC	8019	31.1%	56.7%	73.8%	87.2%	92.1%	95.2%
HS2	4	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 8-10: Change in V/C ratio of stops from HS2 to WCML Ext

Line	Δ Stops	Δ % Stops below Volume/Capacity Ratio					
		<.25	<.5	<.7	<.9	<1	<1.1
Lines Into Euston	-18	-0.2%	3.4%	2.9%	0.0%	0.0%	0.0%
Victoria SB	0	0.0%	0.0%	3.7%	0.0%	3.7%	0.0%
Northern Bank SB	0	0.0%	-1.1%	0.0%	2.2%	0.0%	0.0%
Northern Charing SB	0	0.0%	1.8%	1.8%	0.0%	0.0%	0.0%
Piccadilly SB	0	0.0%	0.4%	0.0%	0.4%	0.0%	0.0%
Crossrail EAST	53	-1.6%	3.0%	1.5%	-1.8%	0.1%	0.0%
Hammersmith, Circle, Me	0	1.3%	0.6%	3.2%	0.6%	0.0%	0.0%
Other Underground	53	0.4%	0.1%	-0.2%	-0.1%	0.0%	0.0%
DLR	0	0.6%	-1.9%	-0.6%	0.0%	0.0%	0.0%
Other Overground	14	1.9%	2.8%	0.8%	-2.3%	-0.3%	0.0%
Other TOC	-17	-0.2%	-0.5%	0.1%	0.0%	0.0%	-0.1%

Table 8-11: Change in Movements near Euston and Euston Square from HS2 scen to WCML Ext scen

		Leaving Station					
		Victoria SB	**NL Bank SB**	**NL Charing SB**	**MCC EB East**	**All**	**Δ VoC**
Entering Station	**HS2**	-51	124	-162	404	194	0.01
Entering Station	**WCML**	-100	-613	-153	-1,301	-4,282	-0.21
Entering Station	**Victoria SB**	24	1	0	0	6	0.00
Entering Station	**NL Bank SB**	32	15	0	0	46	0.00
Entering Station	**NL Charing SB**	0	0	-42	2	-46	0.00
Entering Station	**MCC EB East**	0	0	0	646	69	0.00
Entering Station	**All**	-184	-437	-331	-591		
	Δ VoC	-0.01	-0.02	-0.02	-0.02		

NL = Northern Line; MCC = Metropolitan, City, Hammersmith; VoC = Volume to Capacity

8.2.2 Accessibility

The WCML extension is expected to improve access to jobs from Hertfordshire. One part of this benefit may be derived from faster connections to major job center in Westminster, City of London, and Canary Wharf, while another part of the benefit may be derived from less crowded vehicles and the avoidance of difficult transfers.

Figure 8-4 shows that a number of the zones in Hertfordshire have an increase in weighted access to jobs. The aggregate improvement in Dacorum is over 18% and the aggregate improvement in Watford is over 11% (see Table 8-12). Within central London, there is a modest, .3% increase in access to people. The WCML has mixed effects on the level of access to people at Old Oak Common. On one hand, the WCML project reduces travel times from Hertfordshire, and combined with the benefits of the Overground station, improves the level of access to people. On the other hand, the WCML extension would increase the level of vehicle crowding near the site. An unweighted isochrone accessibility, which is typically used, would have omitted this crowding effect and rated the WCML extension as entirely helpful.

The Overground station at Old Oak Common increases the level of access to Old Oak Common (see Figure 8-4). Although this benefit is eventually offset in part from an increase in vehicle crowding, the zones near Old Oak Common generally show between a 2 and 5 point improvement in access to people, with some zones increasing by over 10 points. However, the Old Oak Common zone with the best walk access to Crossrail actually showed a decrease in accessibility, presumably caused by an increase in crowding on

Crossrail.[37] Again, if further capacity increasing investments, such as Crossrail II, are made in a timely fashion, this eventual crowding may be avoided or mitigated.

[37] This is also the zone had been selected to represent Old Oak Common in the development site tables

Figure 8-4: Percent change in Accessibility from HS2 to WCML Ext

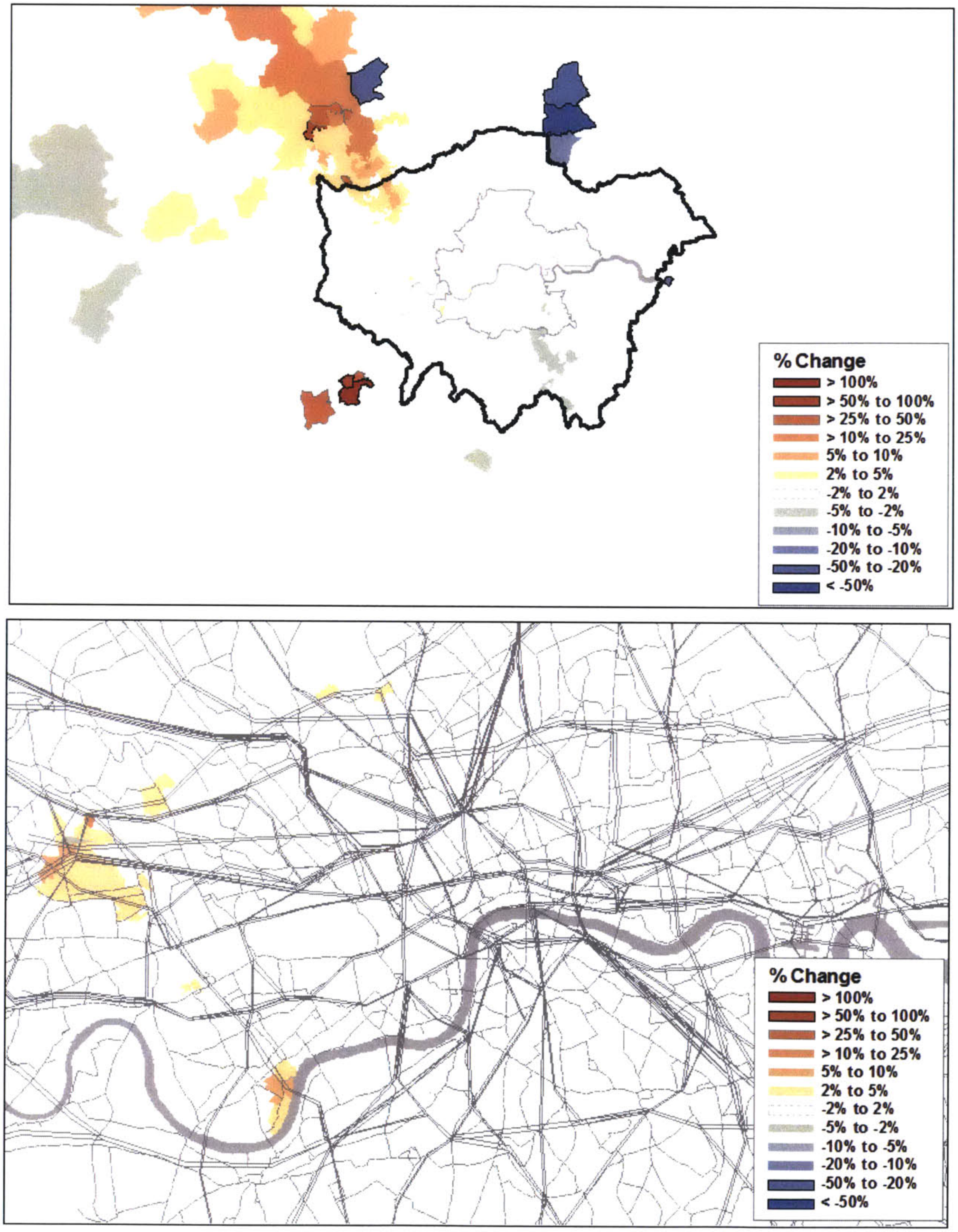


Table 8-12: Aggregate Change in Accessibility from HS2 to WCML Ext

	Jobs	People	% Change Jobs	% Change People
Central London	1,491,001	1,384,872	0.1%	0.3%
Isle of Dogs	739,465	1,022,936	-0.1%	0.4%
Inner London- Ring	723,419	1,000,294	0.1%	0.4%
Inner London-All	774,249	1,194,179	0.1%	0.4%
Outer London-Ring	351,548	583,931	0.3%	0.3%
London-All	518,265	944,875	0.2%	0.4%
Camden	1,036,224	1,331,949	0.5%	0.2%
City of London	1,703,257	1,494,405	0.1%	0.3%
Croydon	258,308	581,018	-0.4%	0.3%
Ealing	486,412	705,992	0.6%	1.1%
Enfield	313,510	555,655	0.1%	0.0%
Greenwich	363,624	618,213	-0.2%	0.0%
Hackney	828,848	1,131,422	0.2%	0.3%
Hammersmith	776,192	974,201	0.7%	1.1%
Harrow	397,114	620,849	2.2%	0.5%
Havering	258,826	479,913	0.3%	0.2%
Merton	404,974	733,699	0.2%	0.3%
Newham	509,946	853,189	0.3%	0.3%
Richmond	340,804	535,066	0.0%	-0.3%
Southwark	865,340	1,100,513	-0.2%	0.2%
Dacorum	137,430	230,675	18.8%	2.1%
Dartford	78,835	134,323	-0.1%	-1.4%
Epsom and Ewell	93,787	223,036	0.2%	-0.2%
Slough	163,967	276,045	-0.2%	1.6%
Watford	280,187	421,255	11.1%	0.6%
Welwyn Hatfield	153,917	329,040	0.4%	0.1%
Wycombe	9,050	22,079	0.4%	-0.4%

Table 8-13: Change in Accessibility at Development Sites from HS2 to WCML Ext

Development Site	Jobs	People	% Change Jobs	% Change People
Old Oak Common	830,905	1,013,836	-13.3%	-4.0%
Euston	1,676,136	1,593,419	0.8%	-0.1%
Kings Cross	1,571,255	1,586,087	0.4%	0.1%
Stratford City	893,174	1,401,096	0.5%	0.6%
White City	602,092	598,030	0.6%	2.6%
The Royals	475,077	688,581	0.3%	0.2%
Canary Wharf	1,022,800	1,189,377	-0.1%	0.4%
Silvertown Quay	515,703	836,313	-0.6%	0.3%
Greenwich Peninsula	518,258	785,663	0.2%	0.1%
Ruskin Square	369,124	819,425	-0.4%	0.3%
9 Elms	833,951	846,197	0.0%	0.2%
Earls Court	1,072,340	1,192,776	0.7%	0.8%
Chiswick Park	636,085	817,740	0.0%	-0.8%
Waterloo	1,539,275	1,291,702	0.0%	0.1%
Paddington	1,446,556	1,467,735	-0.9%	1.5%
Wembley	437,278	662,366	1.0%	1.0%

8.2.3 Select Link

Although the WCML Extension and proposed Overground Station investments would not increase vehicle capacities by a significant amount, they will redistribute demand within London and could either improve or exacerbate volume to capacity ratios.

There is a modest effect on vehicle crowding heading into central London (see Table 8-14). The percentage of trips that crosses a bottleneck increases by about a point, which is caused by an increase in Crossrail crowding levels. Origins in Hertfordshire see an improvement in crowding levels. The percent of trips starting in Dacorum that must board into a bottleneck decreases by 10 percentage points. Overall, the WCML extension in conjunction with the HS2 project appears to have a large, positive impact on crowding levels for demand originating in Hertfordshire.

Table 8-14: Change in Select Link V/C Ratio Distribution from HS2 to WCML Ext

	Δ % TIME AT VOLUME/CAPACITY RATIO						Δ % Thr Bottle	Δ % Brd Bottle
DESTINATIONS	**<.25**	**<.5**	**<.7**	**<.9**	**<1**	**<1.1**	**Perc**	**Perc**
City of London	-0.2%	0.0%	0.2%	-0.2%	0.0%	0.0%	1.1%	0.0%
Central London	-0.2%	0.3%	0.2%	0.0%	0.0%	-0.1%	0.9%	-0.2%
Isle of Dogs	0.1%	0.7%	1.1%	0.2%	0.0%	-0.1%	1.4%	0.1%
Inner London- Ring	-0.2%	0.4%	0.2%	-0.1%	0.0%	-0.2%	0.4%	0.3%
Inner London-All	-0.2%	0.3%	0.2%	0.0%	0.0%	-0.2%	0.7%	0.0%
Outer London-Ring	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.4%	0.0%
London-All	-0.2%	0.3%	0.2%	0.0%	0.0%	-0.1%	0.6%	0.0%
ORIGINS	**<.25**	**<.5**	**<.7**	**<.9**	**<1**	**<1.1**	**Perc**	**Perc**
Inner London	0.2%	0.2%	0.0%	0.0%	0.1%	0.0%	0.2%	0.0%
Outer Ring	0.2%	0.2%	0.0%	-0.1%	0.1%	0.0%	1.3%	0.1%
Commuter Ring	0.1%	0.5%	1.0%	-0.2%	0.1%	0.0%	-0.9%	0.1%
Camden	0.2%	0.7%	0.2%	0.6%	0.0%	0.0%	0.5%	0.1%
Croydon	0.6%	-0.5%	-0.3%	-1.4%	0.0%	-0.2%	0.6%	1.6%
Ealing	0.3%	-0.3%	-0.1%	-0.9%	0.0%	0.0%	9.2%	0.0%
Enfield	0.0%	0.0%	0.0%	0.2%	0.1%	0.0%	0.0%	0.0%
Greenwich	0.0%	-0.5%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%
Hackney	0.3%	0.8%	0.5%	0.0%	0.1%	0.0%	-0.3%	0.0%
Hammersmith	0.5%	-0.1%	-0.4%	-0.1%	0.0%	0.0%	1.0%	-0.3%
Harrow	0.2%	2.4%	1.3%	0.8%	0.0%	0.0%	-1.0%	0.0%
Havering	0.2%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Merton	0.1%	0.4%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
Newham	0.0%	-0.1%	0.4%	0.0%	0.0%	0.0%	0.0%	-0.1%
Richmond	0.8%	0.6%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Southwark	0.2%	-0.2%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
Dacorum	-0.7%	6.7%	18.5%	1.5%	0.1%	0.0%	-7.0%	-9.3%
Dartford	0.0%	-0.1%	0.6%	0.0%	0.0%	0.0%	-1.4%	-0.1%
Epsom and Ewell	0.2%	0.2%	0.0%	-0.4%	0.0%	0.0%	1.4%	0.4%
Slough	0.0%	0.2%	-0.7%	-8.7%	0.1%	0.1%	1.0%	0.0%
Watford	1.5%	2.6%	9.3%	1.2%	0.0%	0.0%	-4.0%	-0.3%
Welwyn Hatfield	0.0%	0.1%	0.1%	0.1%	0.2%	0.0%	0.0%	0.0%
Wycombe	0.3%	1.1%	0.8%	0.5%	0.1%	-0.7%	0.0%	9.3%

Thr = through; Brd = Board; Bottle = Bottleneck

8.2.4 Cordon Capacity

The WMCL Extension and Overground Station will have a small impact on the cordon capacity of some districts in the southeast of England by changing the location of stops on routes.

The clear case where cordon capacity will be raised within London, is represented by Hammersmith and Fulham, which in addition to the new Overground stop, have a larger cordon capacity boost from the WCML extension. However, the net effect on the cordon V/C is about zero, as the WCML extension brings in more demand along with the boost in capacity. The biggest loss in cordon capacity occurs due to the decreased number of vehicles running into Euston. This loss in capacity is mostly offset by a proportional decrease in demand and the change in the cordon V/C ratio is about zero.

Table 8-15: Change in Cordon Capacity from HS2 to WCML Ext

	All Trains			Trains Excluding TOCs		
	Δ Demand	Δ Supply	Δ % VoC	Δ Demand	Δ Supply	Δ % VoC
Central London	-4,778	-14,201	0.5%	900	0	0.2%
Inner London	1,163	602	0.1%	5,654	14,802	-0.6%
London	367	235	0.1%	5,016	12,002	1.7%
Isle of Dogs	175	0	0.2%	52	0	0.1%
Camden	-5,035	-9,307	0.1%	-674	2,240	-0.5%
City of London	-1,284	-2,433	0.1%	-50	0	0.0%
Croydon	2	-694	0.4%	0	0	0.0%
Ealing	325	1,120	0.0%	268	1,120	-0.1%
Enfield	10	0	0.0%	0	0	0.0%
Greenwich	92	-2,171	0.6%	0	0	0.0%
Hackney	313	2,240	-0.6%	376	2,240	-0.8%
Hammersmith	10,091	20,807	0.1%	10,966	20,420	0.6%
Harrow	80	8,866	-2.0%	1,357	12,002	-1.5%
Havering	34	0	0.0%	24	0	0.0%
Merton	47	-231	0.1%	-158	0	-0.5%
Newham	130	1,120	-0.1%	45	1,120	-0.2%
Richmond	-16	560	-0.4%	-104	560	-2.5%
Southwark	-1,456	-5,810	0.5%	-9	0	0.0%
Sutton	-81	-1,041	1.0%	0	0	-
Tower Hamlets	304	1,120	-0.1%	219	1,120	-0.2%
Waltham Forest	-4	0	0.0%	-4	0	0.0%
Westminster	-714	0	-0.1%	-849	0	-0.2%
Dacorum	52	2,865	-7.6%	0	6,001	-
Dartford	-19	-844	1.1%	0	0	-
Epsom and Ewell	-7	-347	0.9%	0	0	-
Slough	62	0	0.2%	28	0	0.2%
Watford	578	10,685	-7.7%	4,058	18,003	8.0%
Welwyn Hatfield	0	0	0.0%	0	0	-
Wycombe	2	0	0.0%	0	0	-

9 CONCLUSIONS

This chapter reviews the major research findings, and it is divided into four sections:

1. The first section contains a synopsis of the research and presents the general findings;
2. The second section discusses how the research findings could help inform transportation and land use policy decisions that London may face, such as how London should condition its support for HS2 and whether London should advocate for an early implementation of Crossrail II;
3. The third section discusses the research limitations and presents ideas to address these shortcomings;
4. The fourth section presents research ideas that were not discussed in the third section.

9.1 Synopsis and General Findings

Effective transportation planning in growing cities and regions requires a clear understanding of system capacity constraints. An underinvestment in capacity could limit access to productive urban centers and constrain the economy. Public transportation, particularly heavy rail, can supply the capacity needed to accommodate growth in dense business districts.

Past research and modeling efforts have predicted large productivity benefits from public transportation investment. Chatman and Noland (2014) examined American cities and found that a 10 percent increase in transit seats was associated with productivity benefits between $1.5 million and $1.8 billion per metropolitan area yearly. The Crossrail business case found that transportation investment can create large productivity benefits beyond what is captured in traditional appraisal, based on travel time savings. Applying agglomeration elasticities developed by Graham (2007) and others, the Crossrail business case predicted productivity benefits, above travel time savings, in the range of £70 billion and £470 billion over 60 years when changes in employment density are also considered (TfL, 2011a; see section 2.4.3).[38]

This research considered the spatial relationship between capacity constraints in large public transportation systems and user and land use impacts. A poor understanding of this relationship could lead to inefficient investment decisions.

[38] The lower bound, £70 billion, includes the "move to more productive jobs" benefit, but uses values of time suggested by DfT and assumes that the apparent job growth in central London and the Isle of Dogs is caused by job relocations. The upper bound, £470 billion, uses values of time suggested by TfL and assumes that all of the new jobs represent "additional" growth (see TfL, 2011a; section 2.4.3).

A transit assignment model was developed to:

1. Examine how biases in common modeling practices, such as lax enforcement of capacity constraint or controlling volume to capacity ratios through link-based crowding penalties, could distort our understanding of the spatial relationship between crowding and economic impacts;
2. Review established methods, based on static assignment, for measuring system capacity constraints; explore new ideas for measuring capacity constraints, with a focus on identifying land uses that contribute to crowding problems and land uses that are vulnerable to crowding problems;
3. Examine how the HS2 project and complementary investments, such as the West Coast Main Line Extension, could benefit London and the surrounding commuter towns by relieving vehicle crowding or improving intra-regional accessibility.[39]

This research considered two biases in economic analysis from the improper enforcement of capacity constraint. One bias, reviewed in section 7.1, occurs from the lax enforcement of capacity constraint. As indicated in Figure 7-2, the accessibility level of land uses varies considerably and asymmetrically when capacity constraints are not enforced.

The second bias, reviewed in section 7.2, occurs when maximum vehicle loading is limited through exponentially increasing link-based[40] penalties, instead of being limited through stop-based penalties that apply only to those attempting to board. A link-based penalty is appropriate for modeling discomfort effects from crowded vehicle conditions and for representing long dwell times, but is not appropriate for modeling denial of service. When an exponentially increasing link-based penalty is used to control crowding levels, all passengers are valid candidates for being re-assigned to different routes, rather than only those passengers who need to board the vehicle. However, as discussed further in section 9.3, there can be important asymmetries in the conditions that passengers face during the AM and PM peaks. For example, AM commuters traveling from High Barnet to Bank would almost certainly get a seat, whereas during the PM return trip from Bank to High Barnet, these same commuters might face a denied boarding and would likely need to stand in crowded conditions.

[39] This research considered intra-regional accessibility benefits, such as between Hertfordshire and Westminster. However, due to data and time constraints, this research did not explicitly consider inter-regional accessibility benefits, such as between London and Birmingham.

[40] A link-based penalty applies to all users who cross the link, including those already on the vehicle and those who just boarded. A stop-based penalty only affects new boarders.

Relying on link-based penalties in model application can distort the spatial impacts of capacity constraints in several ways. For origin-destination pairs that require boarding or transferring to crowded vehicles, the modeled disutility of the journey will be biased downward. Therefore, the modeled attractiveness of these land uses will contain an upward bias. Also, when only link-based penalties are used, models cannot represent the fact that these OD pairs are in a precarious position and are vulnerable to further system growth, such as AM trips between Euston and Victoria. Conversely, for origin-destination pairs that do not require boarding or transferring to crowded vehicles, the modeled disutility of the journey will be biased upward. An example of this is the modeled AM trip from Walthamstow Central to Victoria Station.

Figure 7-4 shows how the accessibility of land uses downstream from the Euston bottleneck of Victoria Line southbound (VLSB) are disproportionately impacted when the stop-based penalty is removed, suggesting that the attractiveness of these land uses is biased upward when using the common link-based technique is used.

Three established measures for measuring capacity constraint were reviewed in chapter 6: volume to capacity analysis, select link analysis, and cordon capacity analysis. The traditional volume to capacity analysis was shown to be useful for highlighting problematic links in London's public transportation system (see Figure 6-1). However, this technique was of limited value for making judgments about how capacity constraints affect trip patterns, travel time savings, accessibility, and land use potential.

Select link analysis (see section 6.2), as suggested by Buchanan and Volterra (2009) in developing the Crossrail business case, can be used to illustrate the crowding challenges facing different origins and destinations. To be specific, Buchanan and Volterra modeled the distribution of maximum in-vehicle crowding levels that users experience traveling to either central London or the Isle of Dogs (see section 2.3.3). This technique is useful for understanding the discomfort effect of traveling in crowded vehicles. If in-vehicle discomfort were to approach unsustainable levels, households and businesses may need to rethink location decisions, potentially leading to a loss of agglomeration or productivity benefits. As commutes become very unpleasant, businesses may need to pay increasing "wage premiums" to remain on equal competitive footing in attracting talented employees (Weisbrod and Reno, 2009). Furthermore, if commuters feel compelled to drive to work in order to escape the regular delays and discomfort of using crowded public transportation systems, then the required automobile expenditures would reduce their savings or limit other spending.

The cordon capacity measure, which is the ratio of the flow going into a zone against the maximum possible flow that can go into that zone, can be used to identify land uses that suffer from severe crowding problems. However, as discussed in section 6.3, the cordon capacity measure has a number of limitations and can understate capacity challenges. The measured ratio can be sensitive to the defined boundaries, as small changes to the defined boundaries can cause significant changes in the ratio. On the other hand, for cases where the measured ratio approaches one, the cordon capacity measure makes a compelling argument for the difficultly or impossibility of further growth. For example, the cordon capacity measure was used in the Crossrail business case to predict that transportation capacity constrains would cause 27,000 jobs that were forecasted to locate in central London or locate the Isle of Dogs by 2026 to actually locate elsewhere (TfL, 2011a).[41]

This research argued that accessibility measures should be sensitive to crowding effects and accessibility analyses should be referenced in strategic discussions about capacity investment. Accessibility is often the key variable in transportation and land use models, such as LonLUTI, that forecast economic impacts and land use effects. Any bias in how the accessibly measure is modeled, such as those introduced by applying link-based crowding penalties, would bias the economic forecasts. Furthermore, the "effective density" measure prescribed by the UK Department for Transport for calculating agglomeration benefits (see DfT, 2013b), closely resembles a gravity measure of accessibly. Therefore, these important economic calculations will be biased if accessibility is measured inappropriately.

The accessibility measures in LonLUTI and the effective density measure are sensitive to crowding effects, even if there is potential to misrepresent these crowding effects. On the other hand, the unweighted isochrone accessibility measure, which is commonly studied by transportation planners and policy makers, is entirely insensitive to crowding effects. An overreliance on the unweighted isochrone could distort thinking and bias investment strategy away from projects that deliver capacity benefits in favor of projects that connect new land uses to the public transportation system. Another concern, as discussed in section 6.4, is that unweighted isochrones can overstate the benefit of projects that could, on one hand, better connect land uses to the public transportation system, but on the other hand, exacerbate crowding problems.

This research presented a few ideas for how select link analysis could be enhanced to attain deeper insight into which OD pairs exacerbate crowding problems and which OD pairs are vulnerable to crowding

[41] See section 2.3.3. TfL also did a sensitivity test on the possible GDP effect of these 27,000 jobs being lost from the UK instead of being located elsewhere in the UK

problems. If bottlenecks[42] in the system are first defined, then select link analysis can be employed to show which OD pairs are sending demand through the bottleneck and which OD pairs require a (difficult) boarding or transfer within a bottleneck. As discussed in chapter 4, OD pairs that send demand through a bottleneck are at least exacerbating crowding problem. However, these OD pairs may or may not also be vulnerable to crowding problems. If these OD pairs are not vulnerable to crowding problems, then they can grow in an unconstrained manner and pass the disbenefits on to others. For example, the Walthamstow Central to Victoria Station OD is not vulnerable to capacity challenges in the AM because passengers can get a seat. If this particular OD grows, then the crowding disbenefits would be passed on to other users and land users. On the other hand, OD pairs that require users to board within a bottleneck are vulnerable to further crowding and are at risk of suffering negative economic consequences from further system growth. Finally, OD pairs that require passengers to stand in crowded conditions are both exacerbating crowding problems and are vulnerable to crowding problems.

Desire lines can be used to present a two-dimensional representation of the select link analysis (see Figure 6-2). This two-dimensional representation indicates that for a given destination (origin), only a subset of origins (destinations) are contributing to the crowding problem, an important fact that is not immediately clear when analyzing a table.

9.2 London Implications

This section discusses how the research findings could help inform transportation and land use policy decisions that London may face. Three planning scenarios are reviewed:

- The "No Build" scenario, which is a 2041 planning scenario that does not include the HS2 investment;
- The "HS2" scenario, which is a 2041 planning scenario that includes HS2;
- The "WCML extension" scenario, which is a 2041 planning scenario that includes HS2, the West Coast Main Line extension, and a new Overground station at Old Oak Common.

This section presents the results at face value, without stating or repeating important caveats. Section 9.3 then reviews those model inputs and assumptions that limit the robustness of the research findings.

[42] In this research, a bottleneck was defined as a link with a volume to capacity ratio over .9

The modeled conditions for the No Build scenario, presented in chapter 6, show a substantial amount of crowding that affects, in particular, commuter towns and English districts surrounding London. Some of the districts, particularly Dacorum, have a large percentage of trips either passing through a bottleneck or boarding into a bottleneck, which could put a constraint on their growth (see Table 6-2).

Table 6-2 suggests that the capacity constraint resulting on commuter towns could be disproportionately large, as evidenced by the high percentage of trips boarding into bottlenecks and the high percentage of travel time that is spent in crowded conditions. However, in absolute terms, ODs in London have the largest number of trips that face crowding challenges. For example, Figure 6-2 suggests that 2500 trips from Islington to Westminster will need to board into a bottleneck. In fact, constraints on trips to Westminster could disproportionately hurt the UK economy, as Westminster contains one of London's large and productive urban centers.

Despite the known weaknesses of the cordon capacity measure, which is reviewed in section 6.3, this measure indicates that crowding levels on vehicles heading into the City of London and the Isle of Dogs are approaching very high levels. Figure 5-12 and Table 5-2 show that the City of London and the Isle of Dogs are expected to see a substantial increase in trip destinations, which means that growth in London may be threatened if transportation capacity constraints are not addressed.

Two justifications are given for the HS2 project. One justification is that HS2 will significantly improve inter-regional accessibility, such as between London and Manchester and between Birmingham and Leeds. This research did not directly consider inter-regional accessibility benefits. The other justification for HS2 is that the West Coast Main Line (WCML) is running out of capacity and HS2 would eliminate the need for running many long-distance trains into Euston, thereby relaxing a vehicle capacity constraint. First, this capacity relief could lead to an increase in the number of passenger trains serving London's commuter market or lead to an increase in the number of freight paths in Great Britain. This increase in the number of trains could deliver accessibility benefits even if passenger crowding levels in WCML vehicles are not an important factor.[43] Second, this capacity relief will tend to reduce crowding levels in vehicles, which may be an important benefit for sections of London's commuter market, such as in Hertfordshire, that face some of the worst crowding problems in the No Build scenario (see Table 8-14).

[43] In other words, increasing vehicle frequency or adding new, distinct paths can deliver benefits even if in-vehicle crowding levels are not substantially reduced.

The HS2 project increases passenger flow on a number of important links inside of London, such as Crossrail, but does not appear to introduce any major problems on other links (see Table 8-2). However, the large boarding penalty that the assignment model applies at Euston may already be limiting how many transfers can occur between HS2 and crowded Underground services, such as Victoria Line Southbound (VLSB) and the Northern Line Southbound (NLSB). While the model may be able to find alternative paths for these HS2 travelers, in reality, if crowding problems on VLSB or NLSB were never addressed, then there would be a percentage of HS2 passenger who would force their way on to the trains, leading to very uncomfortable levels of crowding. In any case, not addressing crowding challenges on VLSB or NLSB would lead to sub-optimal benefits from the HS2 project.

The West Coast Main Line extension would deliver further crowding relief to Hertfordshire (see Table 8-14), as well as improve journey times to key business districts in central London. Combined with the crowding relief from the HS2 project, Hertfordshire stands to see a substantial improvement in intra-regional accessibility if the two projects are completed.

The HS2 project, combined with the Crossrail link to Heathrow, would make Old Oak Common one of the premier sites in the UK in terms of inter-regional accessibility and inter-continental accessibility. However, these benefits were not directly examined in this research. The viability of Old Oak Common as a development site would be greatly enhanced with the new Crossrail station. With very good access to job markets in Westminster and the City of London, the accessibility level of Old Oak Common approaches even that of Canary Wharf (see Table 8-6). While the WCML extension and new Overground station should improve access to Old Oak Common, the benefit may not appear to be entirely positive as these investments may lead to higher levels of crowding near Old Oak Common. In particular, if Crossrail crowding levels are not managed, then Old Oak Common's full potential may not be realized. However, an early implementation of Crossrail II could accommodate enough new growth in London so that Crossrail service does not suffer from severe crowding.

An early introduction of the WCML extension would at least facilitate reconstruction of Euston Station and deliver some crowding relief to VLSB and NLSB, forestalling problems until a more robust solution is identified, such as Crossrail II.

9.3 Research Limitations and Potential Solutions

This research is an attempt to highlight certain aspects of the spatial relationship between capacity constraints in large public transportations systems and economic impacts. However, a number of methodological simplifications were made due, in part, to time and resource constraints. In particular, the assignment model was not formally validated against observed data and further sensitivity tests should be performed on a number of the key inputs and assumptions. The choice of a simple but robust tool, based on static assignment, has facilitated multiple analyses at different levels of detail in an attempt to balance the complexity of the modeling exercise with the professional judgment of the analyst.

This section discusses the research limitations, their implications, and how they could be addressed. There are three sub-sections:

1. The first sub-section describes methodological limitations;
2. The second sub-section discusses how empirical data could be used to enhance and validate the model;
3. The third sub-section describes what sensitivity tests should be performed.

9.3.1 Methods

PM Transit Assignment

The AM assignment period (7AM-10AM) was used for analysis. Punctuality is very important in the AM because people need to arrive to work on time. However, the PM period should also be considered when assessing the spatial relationship between capacity constraints and economic impacts. The accessibility patterns in the PM period could look very different from the AM. For example, a person making a morning Northern Line trip from High Barnet to Bank could get a seat, but may face a denied boarding in the PM or need to stand in crowded conditions. Even though commuters are generally more time-sensitive in the AM, the PM travel conditions would also be an important factor in determining how commuters feel about their choice of residence.

Scenario Years and Demand Matrices

This research examined 2041 planning scenarios. Even though substantial boarding penalties were applied when volume to capacity ratios approached one (see Figure 5-17), some lines were still assigned trips beyond capacity. While this result may reflect an improper coding of transportation supply, such as not including enough bus service or underrepresenting vehicle capacities, another explanation is that some of the assumed demand in the No Build scenario would never materialize unless capacity constraints are addressed before 2041. Early investments in capacity, such as Crossrail II, could prevent inefficient household and business location decisions and deliver agglomeration benefits to London.

One solution for addressing unrealistic demand matrices is to run the scenarios in small increments from the base year out to 2041, adjusting the matrices as capacity problems are first observed. This type of approach could be used to gain an enhanced look at early intervention options. For example, the benefits to Old Oak Common and Hertfordshire from early access to the WCML extension could be tested in this manner. It might be the case that the predicted 2041 crowding problems near Old Oak Common, as described in section 8.2.1, would not materialize if trips patterns evolve differently due to a new distribution of available capacity, particularly if major investments in capacity, such as Crossrail II, are made in a timely manner.

User-Specific Crowding Penalties

Most assignment algorithms employ a single crowding penalty for each network link that applies to all users. While this might be done to facilitate the assignment process and reduce computer run times, a spatial analysis of crowding impacts could benefit from applying user-specific crowding penalties.

For example, a potential, temporary solution to crowding problems is to run vehicles with fewer seats. However, as shown in research by Wardman and Whelan (2010), the perceived disutility from travel is much lower when passengers have a seat. Therefore, a model that can represent a different disutility from sitting than from standing, might help in evaluating the tradeoffs of running vehicles with fewer seats.

Modeling a wide range of user sensitivities to crowding may also be insightful. Figure 7-2 showed that accessibility levels can change by a significant amount when crowding effects are included. However, this represents the change that an average network would perceive. Certain types of commuters, such as young professionals, might be relatively insensitive to crowding levels, whereas other network users, such as the elderly or disabled, might be quite sensitive to crowding levels. An accessibility analysis applying different crowding sensitivities could reveal that some land uses are attractive for crowding-insensitive types, but unattractive for crowding-sensitive types. For example, this analysis could help inform location decisions on where to build subsided housing for the elderly.

Station Crowding

A simple representation of capacity constraints and crowding effects within stations can be achieved through applying standard link-based penalties. However, there is a large, one-time cost of coding a detailed walk network.

Bus Headways

Bus headways were assumed to be two minutes. While this assumption overstates the availability of bus capacity, particularly considering how budget constraints may limit the size of the fleet, it is included to represent the fact that public agencies have some ability to scale up bus service in order to meet crowding challenges. In other words, if the model uses long and static headways, then some bus routes will appear to be overloaded, even though, in reality, the public agency has some ability to address the capacity challenge.

Instead of assuming unrealistically short headways, a better way to model bus service might be to explicitly represent the ability to increase headways, subject to budget constraints. Changes in roadway speeds should also be represented.

Dynamic Transit Assignment, Peak-Spreading, Service Irregularities, and Loss in Capacity

Frequency-based static assignment methods were used in this research. Static assignment is generally far faster than dynamic assignment, but suffers from a number of limitations. For example, peak-spreading behavior is more difficult to model. In reality, as congestion grows to severe levels, some passengers would travel earlier or later in the day. While there is some amount of disutility associated with having to shift departure time, the disbenefit from peak-spreading may be smaller than the disbenefit from using severely crowded vehicles, or what static assignment tends to predict whenever the network is overloaded.

While frequency-based models can represent variable dwell times at stations, vehicle movements are not explicitly represented and service irregularities are harder to predict. Dynamic assignment methods can represent these challenges more precisely. As vehicle dwell times grow very large, there will an (inescapable) loss of maximum vehicle frequency, which could lead to a loss in maximum passenger throughput if the optimal vehicle frequency, assuming an efficient level of crowding, is not preserved.

9.3.2 Empirical Data

Model Validation

Due to time and resource constraints, the assignment model was not formally validated against observed results. Therefore, the results should not be interpreted as actual forecasts, but as a demonstration of analysis methods and potential 2041 conditions.

Boarding Penalty

The vehicle boarding penalties were not calibrated to observed data. However, the penalty should reflect more than just the expected wait time based on some probability of a denied boarding. In particular, revealed or stated preference data may be required to capture any disutility from user frustration or aversion to schedule uncertainty.

9.3.3 Sensitivity Tests

Vehicle Capacity

A maximum standing capacity of four people per square meter was assumed in this research. However, according to the Railplan documentation (2006), a standing capacity of up to seven people per square meter is possible, even if commuters are unwilling to tolerate this level of crowding on a regular basis. Sensitivity testing around the maximum crowding level would help put model results into a proper perspective.

In this type of static assignment model, as volume to capacity ratios approach one, the crowding penalty grows to artificially high levels and some users may be forced into taking extreme alternative paths to circumvent the penalty. For example, if relaxing the vehicle crowding constraint to five or six people per square meter caused the weighted travel time for certain ODs to drop substantially, then it is reasonable to conclude that, in reality, people would force themselves onto crowded trains instead of taking an unreasonable alternative path. This type of behavior, users forcing themselves onto crowded trains, contributes to service irregularities and raises safety concerns.

Boarding Penalties

As discussed in section 9.3.2, the boarding penalty should be calibrated against observed data. However, it would also be helpful to understand how sensitive the model is to these penalties. A relevant question for the HS2 project is how many transfers at Euston to VLSB and NLSB are eliminated by the boarding penalty. If the penalty is too great, then an artificially large amount of demand will be pushed to Crossrail or to alternative paths, thereby minimizing problems at Euston. If the penalty is too small, then the model will overstate the willingness of HS2 passengers to force their way onto VLSB or NLSB trains and exacerbate crowding problems.

Demand Assumptions

The future is uncertain and it is a mistake to place too much weight on the assignment results of a single demand matrix. Testing different demand distributions using alternative future scenarios may be insightful.

9.4 Model Application Ideas

Direct Tests of Growth and Crowding Impacts

As discussed in section 4.1, a trip matrix could be systematically varied to measure how growth impacts transportation facilities and land uses. For example, the (rate of) change in accessibility to a site could be measured as either more flow is sent to that site or as crowding levels increase throughout the system. This type of analysis could be used to assess how vulnerable sites are to crowding problems caused by their own growth or caused by general growth. Furthermore, this test could directly reveal whether sites tend to internalize or externalize disbenefits from growth.

There may be a more efficient way to perform this analysis other than through brute-force assignment. However, if static assignment were proved to yield sufficiently accurate and reliable results, then its speed advantage could be leveraged to keep computer run times to a reasonable length.

OD Manageability and Path Choice

This research suggested that some ODs tend to disproportionately exacerbate crowding problems, while other ODs are disproportionately more vulnerable to crowding problems. A next step may be to determine which ODs have reasonable alternative paths and are candidates for introducing (dis)incentives to influence route choice (see section 4.3). Select link analysis, employed in combination with a variable fare matrix, could be used to identify the manageable ODs. For some ODs, there might not be any reasonable alternative path, and it is best to allow these passengers to continue traveling through bottlenecks. For many other ODs, passengers could be incentivized to change their paths.

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APPENDICES

A. List of Acronyms

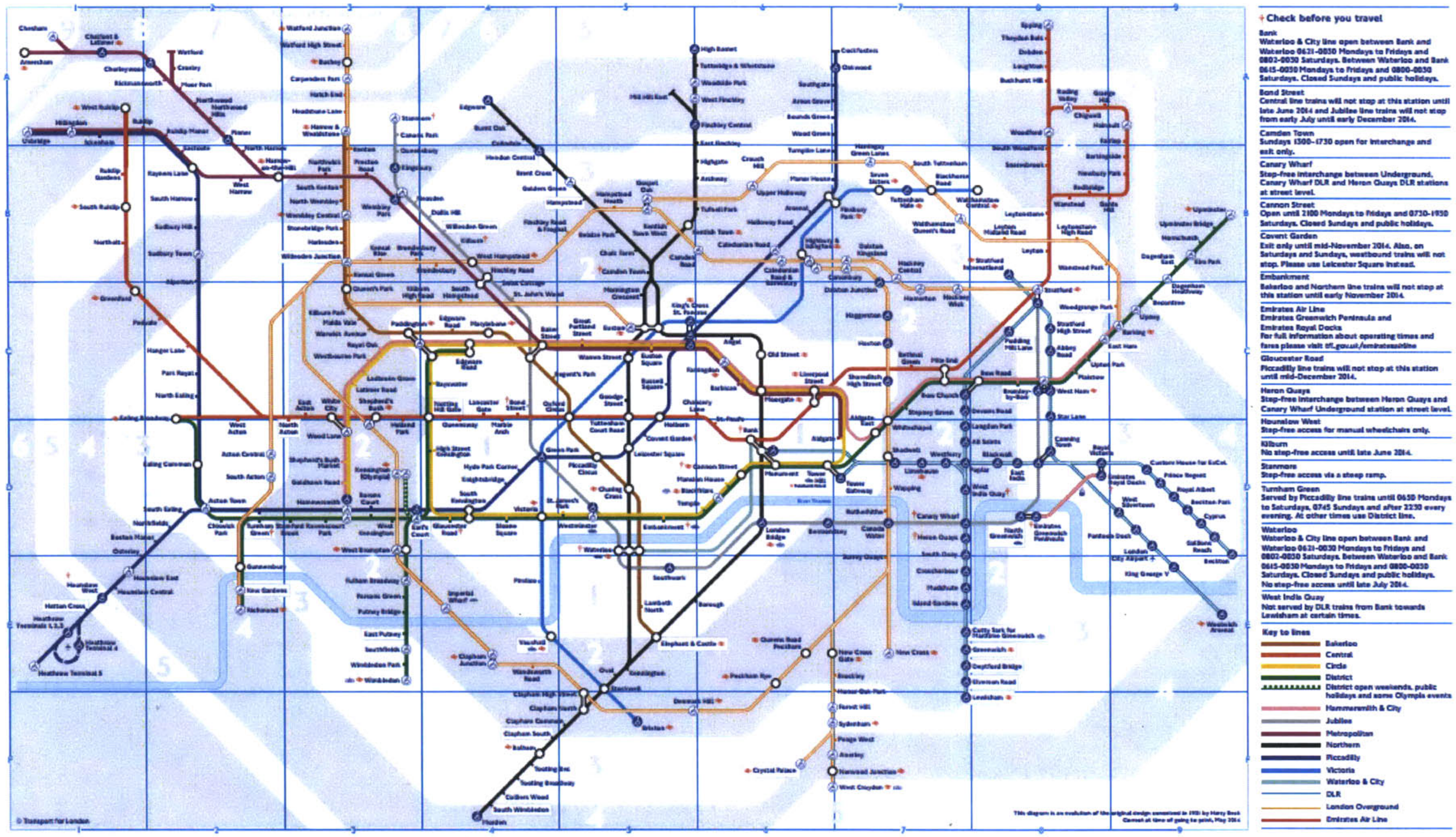
DfT	Department for Transport
ECML	East Coast Main Line
HS2	High Speed 2
HSR	High Speed Rail
GIS	Geographic Information Systems
MSA	Method of Statistical Averages
MSOA	Middle layer of Super Output Area
NLBSB	Northern Line Bank Branch Southbound
NLCXSB	Northern Line Charing Cross Southbound
OA	Output Area
ONS	Office for National Statistics
PT	Public Transportation
TfL	Transport for London
TAZ	Traffic Analysis Zone
V/C	Volume over Capacity
VLSB	Victoria Line Southbound
WCML	West Coast Main Line
WEIs	Wider Economic Impacts

B. Reference Maps

Figure B-1: Map of National Rail Lines

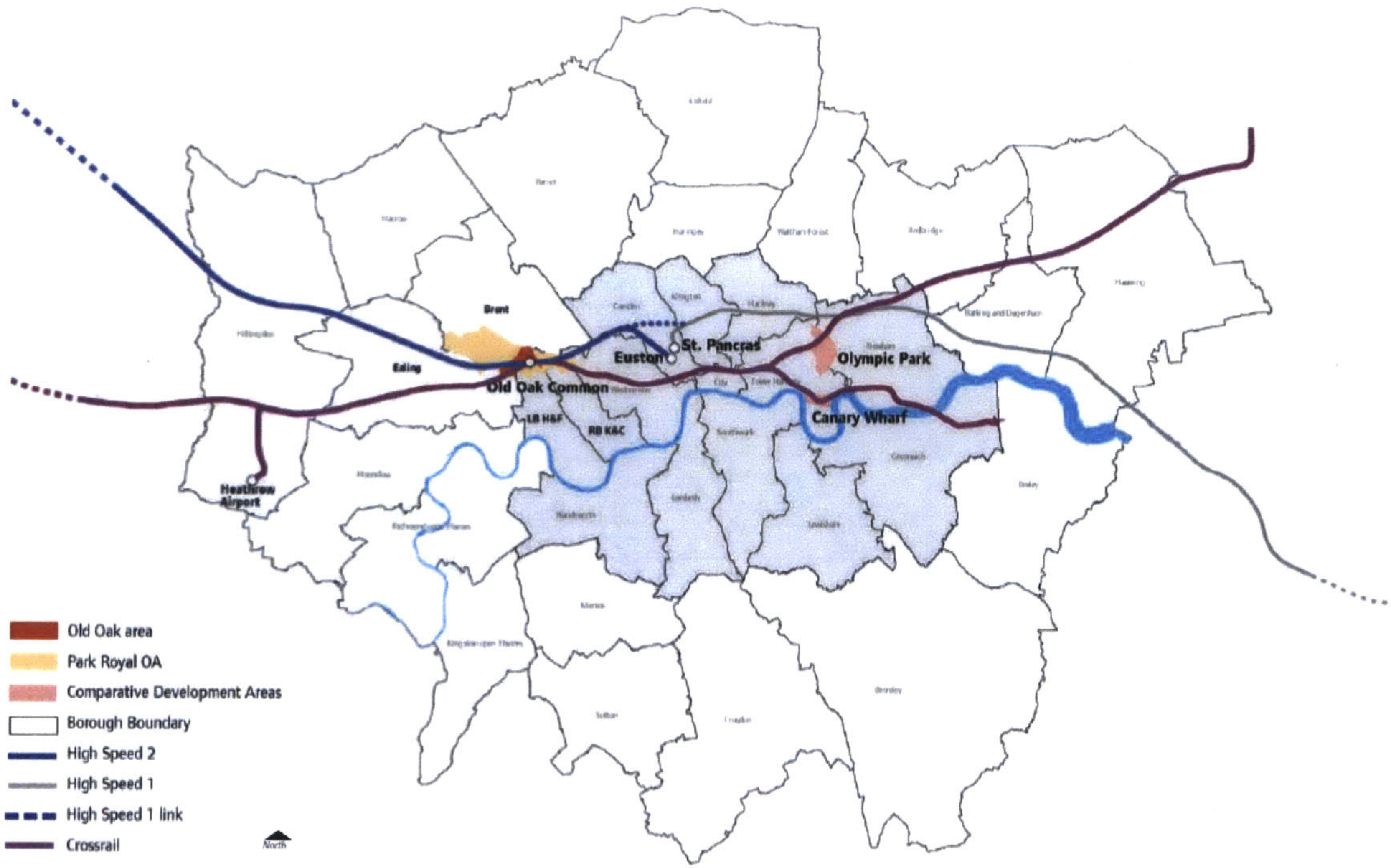
Source: (ATOC, 2013. Retrieved from: http://www.nationalrail.co.uk)

Figure B-2: Map of the Tube



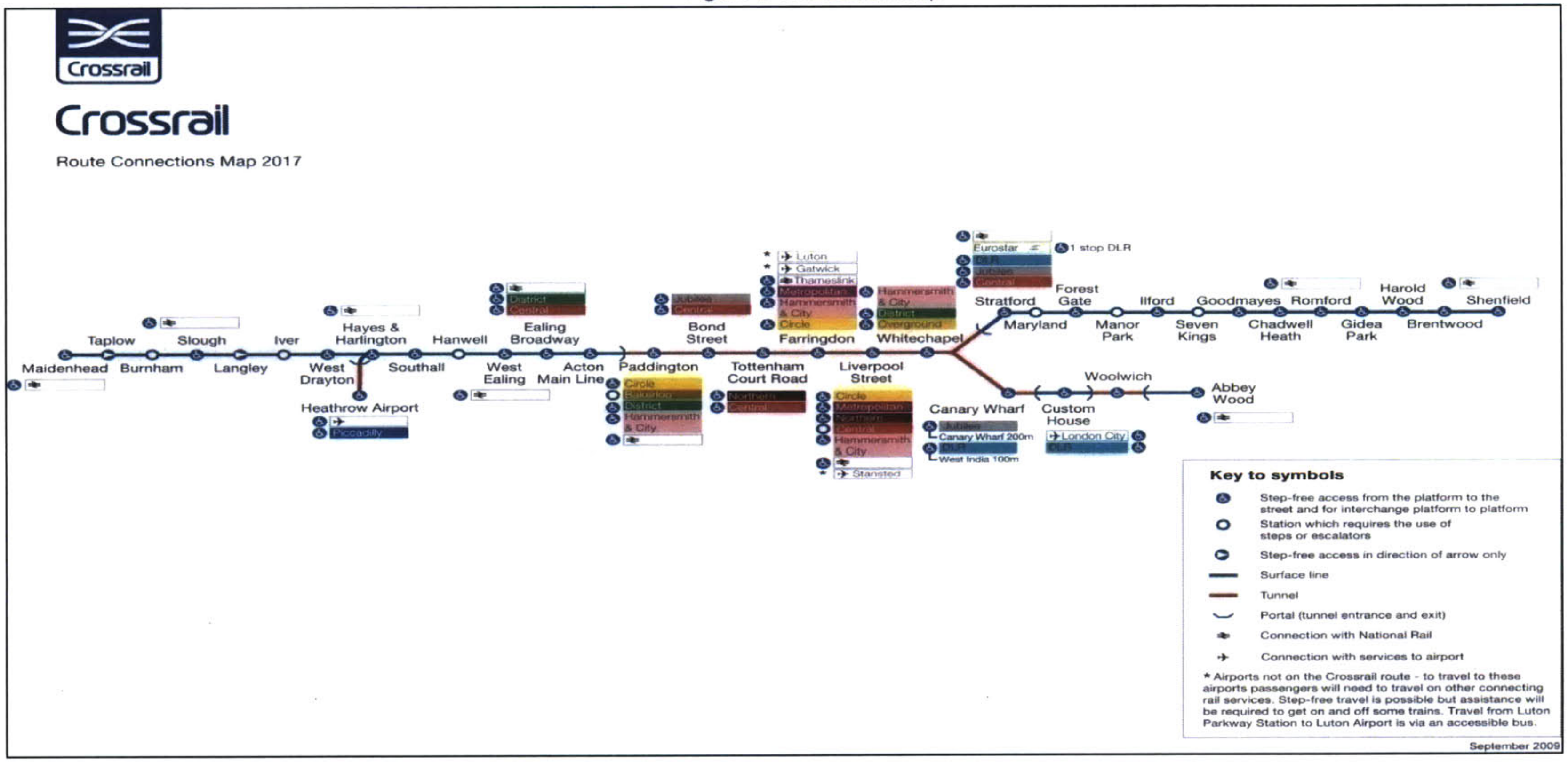
Source: (TfL, May, 2014. Retrieved from: https://www.tfl.gov.uk)

Figure B-3: HS2 Stations



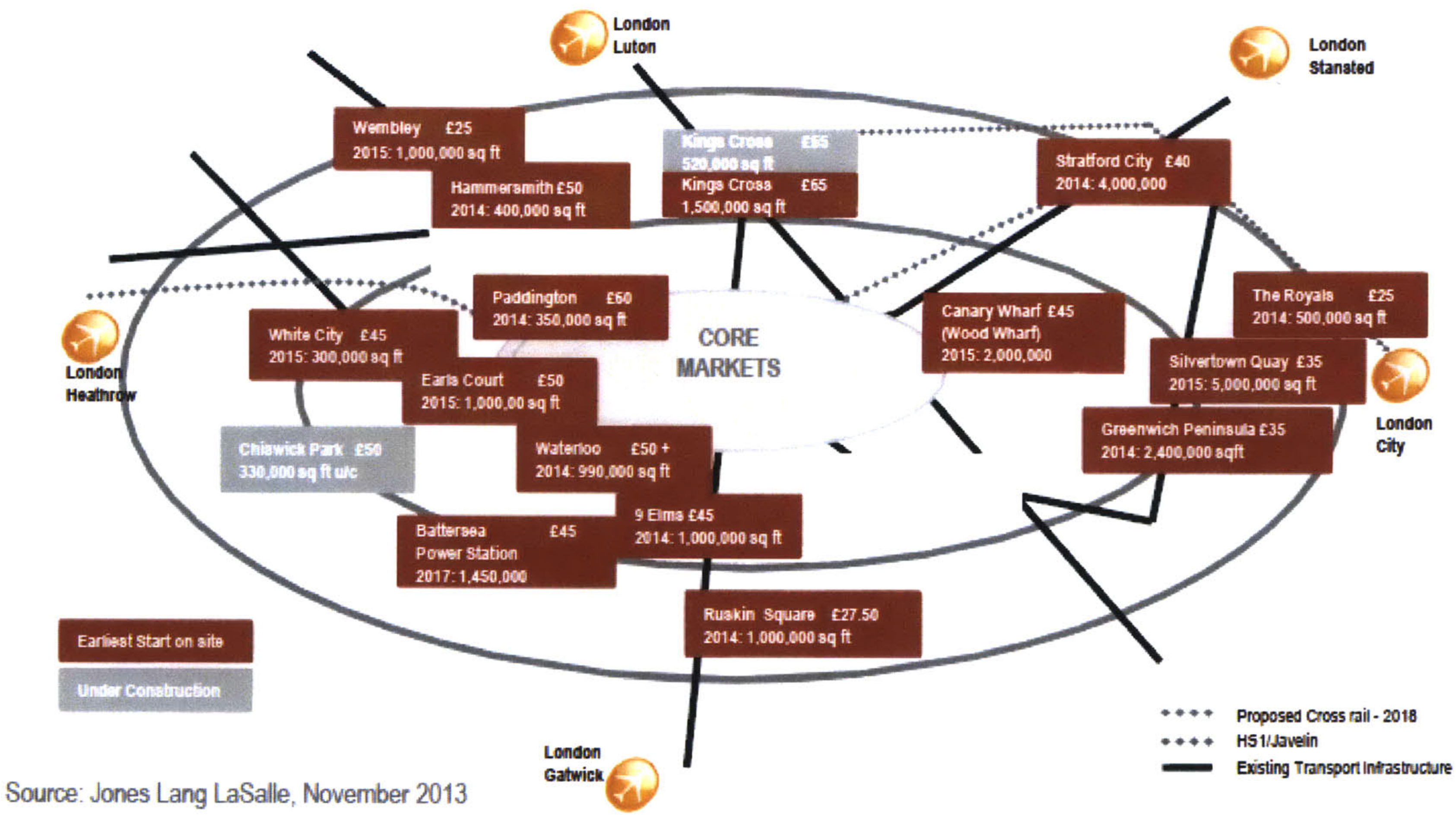
Source: (GLA, 2013)

Figure B-4: Crossrail Map



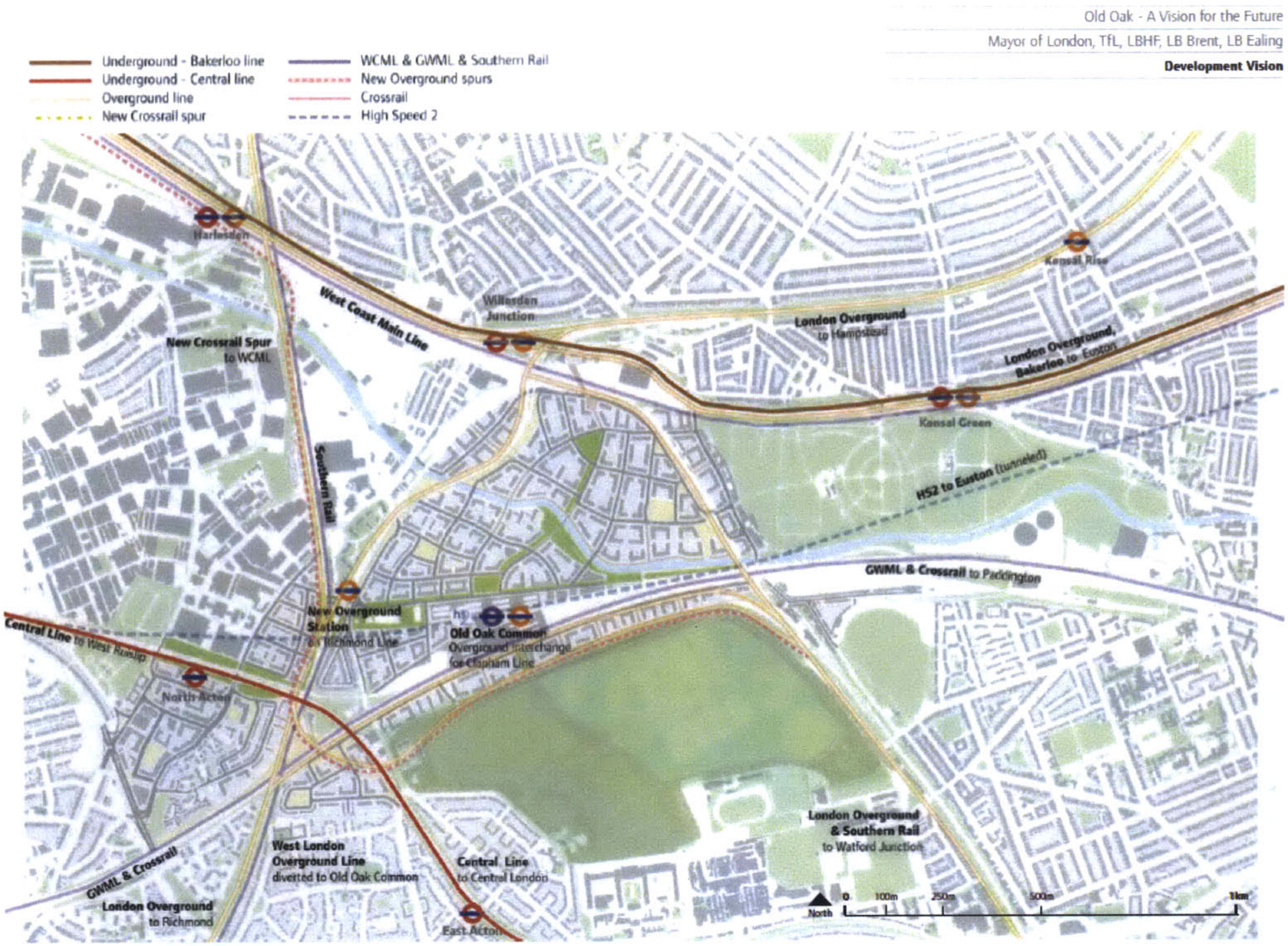
Source: (TfL, 2011b)

Figure B-5: London Development Sites



Obtained From: (Jones Lang LaSalle, 2014)

Figure B-6: Overground Stations at Old Oak Common



Source: (GLA, 2013)

Figure B-7: Growth Vision at Old Oak Common

Source: (GLA, 2013)

C. Technical Model Parameters

Table C-1: TransCAD Assignment Parameters

Assignment Method:	Equilibrium Pathfinder
Iterations:	20
Impedance Alpha:	1
Impedance Beta:	3
Travel Time Weight:	1
Wait Time Weight:	2
Walk Time Weight:	2
Max Access Time:	20
Max Egress Time:	20
Min Initial Wait:	0.5
Max Initial Wait:	60
Min Transfer Wait:	0.5
Max Transfer Wait:	60
Bus Transfer Penalty:	8
Rail Transfer Penalty:	3
Interarrival Parameter:	0.5
Path Threshold:	1
Use All Walk Path:	Yes