Advancing Accessibility:
Public Transport and Urban Space

by

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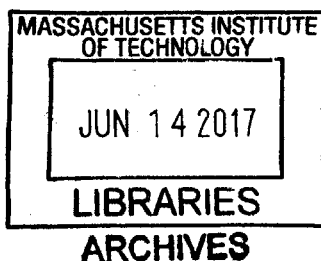Co-Supervisor

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Abstract

After decades of academic research, urban accessibility metrics are beginning to see adoption in transportation and metropolitan planning practice. Such metrics capture the potential for reaching destinations enabled by transport (e.g. number of jobs available within a given commute time), not just the mobility benefits accruing from the use of transport (e.g. time and emissions reductions for a given commute), and have well-established advantages. From a transportation equity perspective, for example, measuring the potential for reaching destinations instead of actual travel avoids bias against groups who travel infrequently due to current or historical barriers to access. This dissertation elaborates on how accessibility concepts complement theories of urban planning and social space before considering two related extensions of accessibility metrics for public transport planning. First, drawing on collaborative planning literature, and using mixed-methods including pre-test/post-test survey designs, various versions of interactive mapping tools were tested in public workshop settings. The outcomes of these workshops suggest that accessibility concepts can improve public involvement in transit planning. Suitability for broad public participation applications, however, requires accessibility to be easily customizable and tailored to constraints that users find salient. Constrained accessibility metrics are the second focus of this dissertation. Adjusting accessibility metrics to account for unreliability in actual transit operations, matching and competition in destination opportunities (e.g. jobs), and capacity in transit networks, may help align these metrics more closely with users' personal experience. Spatial analysis techniques are used to implement some of these adjustments and show that they strengthen correlations with broader urban outcomes of interest, such as employment and use of healthcare resources. The concluding part of the dissertation discusses how these findings can inform substantive and procedural dimensions of public transport planning and urban policy.

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Preface

With the grandeur of the city, and the never-ending crowding of its inhabitants, it is necessary to build countless dwelling-places.

> − Marcus Vitruvius Pollio (15 BCE)
> as the population of Rome approached 1 million inhabitants

Space is always limited, while the demand is always infinite.

> − Former Chinese Deputy Minister of Housing Qiu Baoxing (2015)
> as the population of the Pearl River Delta approached 100 million inhabitants

Cities are undergoing record growth, straining housing and transportation infrastructure in regions around the world. While this scale of urbanization is unprecedented, the underlying attractive forces drawing diverse residents into cities are as old as cities themselves; cities exist because of self-reinforcing agglomeration effects that enhance peoples' access to opportunities (Small and Verhoef, 2007). The greater a city's density and diversity, the greater the potentials for interactions and economies of scale (Krugman (1991), Handy and Niemeier (1997), Chatman and Noland (2014)), for pleasure and productivity (Jacobs (1961),Glaeser and Maré (2001)), for grandeur and "triumph" (Glaeser, 2012).

Grandiosity aside, densification and growth can perversely undermine themselves and urban sustainability. The environmental, ecological, and energy footprints required to support activity across a sprawling built-up region are extensive. Socially, the individualism fostered by cities creates issues of blasé attitudes and aversions (Simmel, 1971); systematic exclusion from access to opportunities along lines of class and race can have devastating effects on residents and a city (McCone (1965), Wilson (1996), Social Exclusion Unit (2003)). Economically, negative externalities and inefficiencies can be centrifugal forces offsetting and even outweighing positive agglomeration externalities. One such inefficiency is transport congestion; further complicating matters is the tautological tendency for such congestion to be concentrated in the locations that are most economically productive and in highest demand (Graham, 2007a).[1]

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[1] Perhaps this issue is captured by Yogi Berra's quip about places that are so crowded that nobody visits them anymore, or the Jevons paradox (see Alcott (2005))

Many cities rely on markets to allocate scarce space to competing development demands, and on transportation to expand the bounds of these markets. Transportation systems facilitate the movement of goods and people at reduced costs, allowing for arbitrage between different land uses across urban space. Describing the fundamental role of transportation, the pioneering Chicago Area Transportation Study stresses a need for "rapid, yet safe and economical, transportation systems" to support "community's strength" (Douglas Carroll Jr., 1959, p. 2).

Notable in this assertion is the primacy of speed. Reduction of costs by saving travel time has been the "stylized fact" driving much of modern transportation planning (Metz, 2008, p. 333). Higher-speed travel can make distant areas, previously inaccessible within given time constraints[2], reachable, enabling urban growth through territorial expansion.

The automobile effectively represented a tripling in intraurban travel speed, so "the area accessible within an hour expanded at least ninefold" and automobiles became dominant in facilitating access in United States cities (Pushkarev and Zupan, 1977, p. 9). As Illich (1970) writes, "Motorized vehicles create remoteness which they alone can shrink. They create distances for all and shrink them for only a few." The extensive space required for automobiles' operation and storage[3] constrains the density they can support. Just as space is scarce in the land market, it is scarce on highways and in parking lots.

While time-efficiency was the centerpiece of 20th century centralized mobility planning, the automobile's relatively inefficient use of space and environmental externalities have encouraged a return to more space-efficient forms of transport (Boarnet, 2013), and toward conceptualizing transportation costs not only in terms of time, but also in terms of other factors such as "quality of experience" (Banister, 2011, p. 957). This shift, away from a narrow quantitative focus on time, privileges a "multitude of shorter journeys, using a combination of active transport modes (walk and cycle) and public transport" to attain accessibility (Banister, 2011, p. 957). The paradigm of speed-enabled territorial expansion, or mobility, is now amended with an emphasis on efficiency-enabled densification, or proximity (Banister, 2008). Yet even with high-capacity buses and trains, crowding effects – for example, passengers vying for space on vehicles – create operational constraints that limit speed and hinder regional connectivity.

Competing demands for space at the levels of cities, networks, vehicles, and individual travelers, especially in intermodal public systems, make for complex challenges of planning and collective action. Political mandates for public involvement and representation, as well as grassroots assertions of a "right to the city" (Soja, 2010), add to these demands. In modernist transportation planning, the problem (time lost due to congestion) and solution (higher speeds through expanded infrastructure) were relatively well-formulated and tractable with specialized technical expertise (Hanson, 2015). In contrast, the interconnected problems and

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[2]For more on individual time constraints, see Hägerstrand (1970) or Chapter 3 in Giddens (1984).

[3]"Worldwide, at least one third of all developed urban land is devoted to roads, parking lots, and other motor vehicle infrastructure... In Los Angeles the figure approaches two thirds" (Southworth and Ben-Joseph, 1996, p. 256).

competing demands of future urban transportation planning entail complexities that may evade even the most ambitious algorithms or systems thinking.

Urban social space, infused with the overlapping practices, meanings, and imaginations of users, rather than the empty "isotropic space of classical (Euclidean/Cartesian) mathematics" alone (Lefebvre, 1991, p. 87), is at the root of these complexities. Urban transportation is "rife with dialectics and contradictions: movement/stability, nodes/links, dwelling/mobility, winners/losers..." (Hanson, 2015, p. 4), and these dialectics are fundamentally spatial. Enhancing movement along a network link may impose varied costs on people living nearby, while this mobility improvement may benefit transient users who live, or will live, far from the link (or vice versa). Such dynamics can make the wins and losses, and winners and losers, of a transportation intervention difficult to grasp for technical experts, let alone community stakeholders.

To account for the overlapping layers of urban space, maps – cartographic representations based on Euclidean distances between locations – are often featured in public involvement materials for transportation projects. Yet transportation's fundamental purpose is to distort the Euclidean relations between places, making reliance on traditional static maps problematic (Shen (2004), Ahmed and Miller (2007)).

Advanced spatial analysis tools, which move beyond traditional static perspectives, promise to improve experts' understanding of urban transportation and its spatial complexities. Unlocking the full potential of such tools also requires engaging "the expertise of the community" (Wigan, 2012, p. 228). This requirement recognizes that expert planners and their models, at least in democratic contexts, do not operate in isolation from prevailing governmental rationalities and power (Altshuler (1965); Flyvbjerg (1998)). How should public discourse and technical analysis about transportation's spatial impacts inform each other? How can stakeholders shape public transport, and how does public transport in turn shape urban space? And how can an orientation toward spaces not as empty containers, but as sets of practiced places and flows, guide the planning and engineering of transport infrastructure? Such questions are the catalysts for this dissertation.

Part I

Overview

Chapter 1

Introduction

The reconstruction of a spatial 'code' – that is, of a language common to practice and theory, as also to inhabitants, architects and scientists – may be considered from the practical point of view to be an immediate task.

– Henri Lefebvre
The Production of Space

To me, accessibility is a very, very powerful frame for all the things we're trying to achieve but we actually haven't found the words yet to do that.

– Stephanie Pollack, Massachusetts Secretary of Transportation
at a Brookings Institution discussion on accessibility metrics in January, 2017

This dissertation seeks to advance the understanding of urban space at three co-constitutive levels:

- The city — primarily a space of places

- The transit network/system[1] — primarily a space of flows

- The transit planning meeting/workshop/hearing — a hybrid space

Distinct discourses – ideologies, measurable objectives, and evaluative techniques – structure each of these levels. Ideologies and normative theories of "the city" abound (Lefebvre (1991), Harvey (1973), Logan and Molotch (2007), Lynch (1984)), though specific objectives

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[1] Transit here refers to fixed-route public transportation services using buses, trains, etc. Transit and public transport are used interchangeably throughout.

or methodologies for evaluating cities are less common. A city's places shape and are shaped by transportation systems, with transit often playing an enduring role (e.g. Warner (2009), Block-Schachter and Zhao (2015)). Compared to the city as a whole, a public transport system generally has more clearly specified objectives and performance indicators (e.g. cost effectiveness metrics, ridership targets, benefit-cost ratios, etc.). Transit is shaped by specific spaces of planning and governance – meetings, workshops, modeling sessions, public hearings, etc. – comprising both a "relational space" of interaction and a "content space" (borrowing from Barron (2003)) of dominant discourses. For example, a content space that frames the role of transit as reducing congestion and attracting "choice" riders may both undermine the standing of households without cars in relational spaces of public participation and ignore important dynamics like induced demand. The planning values, objectives, and methodologies used to plan transit networks are often disjointed, hindering shared understandings of the possibilities of transportation systems generally, and especially transit.

Accessibility to opportunities, also referred to as connectivity or the closely aligned concept of access, can clarify the role transit plays and enable a more coherent understanding of urban space by technical experts and everyday inhabitants alike. Accessibility reflects "how the built environment and individual attributes affect people's access to social opportunities" (Kwan, 2013, p. 1081). Hansen (1959) defines accessibility as a "measurement of the spatial distribution of activities about a point, adjusted for the ability and the desire of people or firms to overcome spatial separation" (p. 73). In a metropolitan region, the most central locations tend to have the highest accessibility, but accessibility gradients rarely radiate outward uniformly due to the uneven nature of transport networks and service. As the attribute of a specific location, accessibility should be specified as: from that location, to a class of opportunities, by a mode of travel (e.g. accessibility of a firm's office to its workforce by transit). As used in this dissertation, *connectivity* connotes metrics aggregated to all locations in a region (e.g. connectivity between jobs and workers), and *access* emphasizes individualized constraints. Universal access, in terms of physical design (e.g. as mandated by the Americans with Disabilities Act) and human-computer interaction (e.g. through screen reader technologies for people with visual impairments), can be important components of urban accessibility, but they are not the primary focus of this work[2].

Geurs and Van Wee (2004) define accessibility as "the extent to which land use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)" (p. 128). They locate accessibility at the center of four travel components: land use, transport, temporal, and individual. I propose a slight revision, on the basis that there are both spatial and temporal dimensions of the land use, transport, and individual components. That is, the attributes of places, flows, and individuals interact through time and space. For example, people might choose to walk through an area during the day, but detour around it at night due to security concerns, depending partly age or gender, which would affect their level of access. Conceptually, this revision places accessibility at the nexus of systems of transport, land use, and identity (see Figure 1.1).

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[2]Accessibility in the sense of universal design is sometimes referred to by eliding the eleven middle letters and using the numeronym a11y

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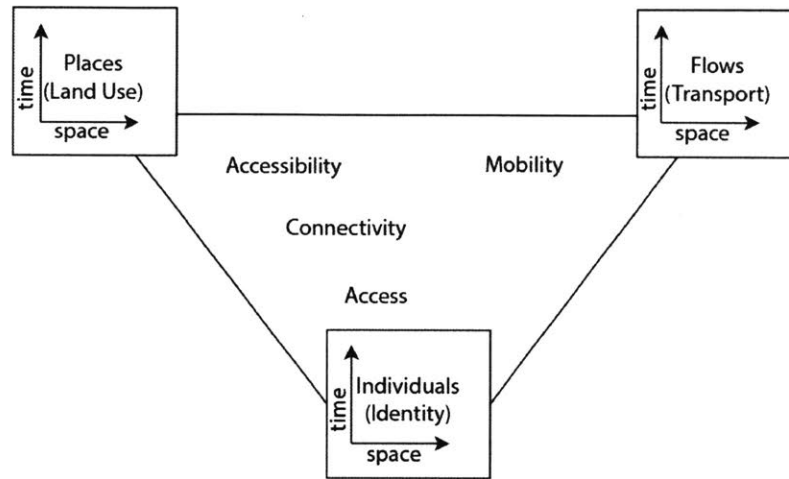
Figure 1.1: The component systems of accessibility

Accessibility objectives appear in a wide range of disciplines and have a long history in urban studies (e.g. Hansen (1959), Foley (1974)). Strong theoretical links exist between accessibility measures and urban planning concerns such as employment and productivity (Boschmann and Kwan (2010), Melo et al. (2016)), as well as segregation and equity (Welch and Mishra (2013), Lucas et al. (2015), Nahmias-Biran and Shiftan (2016), Martens (2017)). Transportation research on accessibility has developed it as an evaluative metric (Wachs and Kumagai (1973), Cervero et al. (1999), Grengs et al. (2010), Levine et al. (2012), Peralta-Quirós and Mehndiratta (2015)); a system goal (Metz (2008), Zegras (2011), Sclar and Lönnroth (2014)); and an overall normative value (Harvey (1973), Soja (2010)). In the 1970s, it was already recognized that "the search for an ideal notion of accessibility has been prolonged" (Forer, 1978, p. 244). This search is still ongoing, with adoption and implementation by only a few practitioners (Thakuriah (2001), Papa et al. (2016), Handy (2017)).

Transport for London's Connectivity Assessment Guide (Transport for London, 2015) reviews the state of the practice in the UK. Catchment analysis is most closely aligned with the notion of accessibility considered in this dissertation, as opposed to access to transport facilities (e.g. Public Transport Access Levels, or PTAL values). Singapore's LTA uses the term "reach" to describe accessibility (e.g. the number of jobs within reach of a given residence), and like TfL it provides an online web mapping tool to help users understand the reach transport enables[3]. While the data and tools to communicate the basic "reach" component of accessibility are now widely available[4], constraints like vehicle capacity are more difficult to integrate, computationally and conceptually.

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[3]Other new tools like the Sidewalk Labs NYC Transit Explorer and Mapzen's Mobility Explorer, also show the growing public appetite for accessibility mapping and metrics.

[4]Many of these tools are freely available as open-source software. An example is discussed in subsection 2.5.6.

A shared conceptual understanding of accessibility is difficult to achieve in part because the term is so widely used in different contexts. Different disciplinary perspectives tend to emphasize different aspects of accessibility. Illustrative examples, working around the conceptual triad in Figure 1.2, follow. Regional travel demand modeling in transport engineering practice focuses primarily on the upper right vertex – the transport system and the spatiotemporal dynamics of flows within it. Transport and urban economics have made progress considering the land use system by valuing wider economic benefits and location-specific agglomeration economies. Developers, urban planners, and geographers consider the distribution of activities and individuals in geographic space. Researchers concerned with social exclusion consider the intersection between residential locations and individual characteristics and demographics (e.g. Preston and Rajé (2007), Currie et al. (2010), Fol and Gallez (2014), Lucas et al. (2015)). Equity advocates and community organizations tend to advocate for improved access for their constituencies along the lines of identities (e.g. Bullard et al. (2004)). Sociologists and anthropologists consider how social and identity systems condition use of mobility systems (e.g. (Sheller, 2004), Ghannam (2011)).

Typical performance indicators in transportation engineering and planning highlight salient concerns of congestion and crowding, which are usually considered implicitly (if at all) in accessibility metrics. The fact that accessibility metrics elide concerns traditionally deemed meaningful impedes the adoption of these metrics. Jurisdictional disjunctures, between local zoning powers and regional transportation agencies, for example, also hinder adoption[5]; in most cases, an agency operating transport has little ability to directly permit housing development. Compounding these adoption barriers are perceptions that accessibility is not easily understandable, politically salient, or actionable for transport agencies when it is largely a function of land use (Pirie (1981), Cervero et al. (1999)).

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[5]At the aforementioned Brookings Institution discussion, Secretary Pollack described this problem as a "span of control" issue.
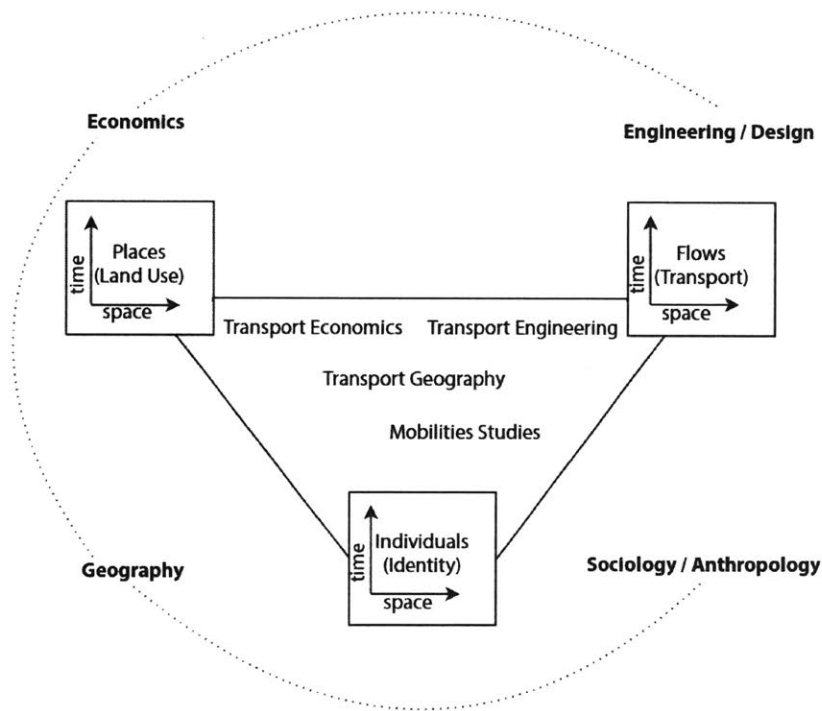
Figure 1.2: A sample of disciplines that use accessibility narratives

1.1 Contributions

The overarching goal of this dissertation research is to advance accessibility concepts and communication tools, making them easily understandable, relevant to broader urban concerns, and supportive of meaningful engagement between diverse stakeholders. I build on past work by deploying tools for representing public transport's spatial impacts in planning practice and stakeholder engagement, as well as improved methodologies for calculating meaningful accessibility measures.

Urban planning theory underpins this work. I also hope this endeavor will contribute to a "spatial code" that could improve the translation between public narratives about transit interventions and the analytic bases of their evaluation. My work to test tools for representing space is conducted collaboratively, using open-source software, and with attention paid to how these tools fit with broader mechanisms of power, rationalization, and spatial techniques of governance (Foucault (1991), Flyvbjerg (1998), Merry (2001)). A related contribution is testing methodologies for quantifying the effectiveness of public involvement, which are underdeveloped especially for transportation (Quick et al., 2015). I seek to take advantage of, and contribute to, what Sheller (2015) identifies as "the recent productive commingling of research" from a wide array of transportation-focused disciplines, which can offer insights into a range of concerns including "the design, building, and appropriation of urban infrastructure," "the embodied experience of streets, stations, and various kinds of

vehicles," and "concerns with accessibility, social exclusion, and the dynamic contestation of the right to the city" (p. 12).

These intended contributions all tie back to space, including the geographically constrained urban spaces of cities, the geometrically constrained spaces of transport rights-of-way, and the ideologically constrained spaces of planning meetings and public hearings. Underlying this work is the belief that improving access to transit planning spaces, transit systems, and the city itself are part of the same fundamental project. In other words, advancing accessibility metrics requires the simultaneous advancement of planning and participation processes that are more open to meaningful engagement with stakeholders and the co-creation of shared understandings of transport's impacts.

1.2   Research objectives

My intended contributions lead to two related objectives:

1. Design representational tools that support communication and highlight accessibility impacts of public transport projects. This objective includes testing how these tools foster mutual learning and enthusiasm in public involvement, and to what extent they do so more effectively than traditional or time-based analyses. Mutual learning is necessary (though not sufficient) for meaningful engagement and co-creation.

2. Improve the representations used in these tools by including adjustments arising from reliability, matching, and capacity constraints. Related hypotheses are that accessibility metrics adjusted for such constraints better align with desired urban planning outcomes, and that the constrained levels of accessibility imply additional disparate impacts on vulnerable populations than would be expected from unadjusted accessibility measures.

These interrelated objectives are informed partly by the orientation of the planning-support system literature toward both usability and usefulness (Te Brömmelstroet and Bertolini, 2012). If planning in the past has relied on technical "black-box" models, research should prioritize not just technical refinements to the models, but also improvements to usability that open the tools and broaden understanding for wider audiences. This prioritization recognizes that tools should help structure not only the content spaces of understanding transport, but also overlapping relational spaces of deliberating about transport.

1.3   Theory and methods

The theories and methods of transportation planning are at the core of this work. As an integrative discipline, planning draws on the methods of engineering, design, and economics

as well as the broader contextualization provided by social sciences including human geography and urban sociology. This dissertation draws on insights and techniques from these disciplines but remains centered in transportation applications. Regarding the two objectives outlined above,

1. Recent literature on collaborative geographic information systems (CGIS) guides the design of the communication tools. These tools are evaluated through iterative testing and mixed-methods experiments drawing on pre-test/post-test designs.

2. Geospatial analysis is used to demonstrate the value of adjusting accessibility metrics to account for various classes of constraints.

1.4 Empirical settings

This work is situated in Western contexts with normative commitments to representative government. While no claims are made about extrapolating findings beyond such contexts, to maximize applicability across settings that share these overarching characteristics, this research is grounded in multiple locations. Greater Boston (US) and Greater London (UK) are the core settings.

Greater Boston, the largest metropolitan region in New England, faces numerous urban transportation planning and funding challenges. The Massachusetts Bay Transportation Authority (MBTA) operates three heavy rail lines (Red, Orange, and Blue), light rail (the Green Line), and 183 bus routes, and it also oversees commuter rail and ferry service operated by private contractors. Much of the system's core rail infrastructure was built a century ago, with two nominal bus rapid transit (BRT) corridors built in the last decade. Though the MBTA is an integrated, regional transit authority, it faces a number of jurisdictional issues[6]. Its funding comes primarily from the Commonwealth of Massachusetts (including through a statewide sales tax), and coordination is required with the Boston Metropolitan Planning Organization, the Massachusetts Department of Transportation, and the 176 cities and towns in its service area. Cities and towns have control over land use through local zoning and development policy. This jurisdictional fragmentation, along with a long history of active civic engagement of Boston residents, makes effective stakeholder engagement tools important for the MBTA. The region's relatively high transit ridership (among US cities) also makes it an apt case for analyses of accessibility by transit.

Greater London has seen a resurgence in public transport ridership and construction, for the 2012 Olympics and with the forthcoming inauguration of Crossrail. Compared to Boston, London's larger and more complex public transport network makes it a good test case for the methodologies and computation used in this dissertation. Transport for London (TfL) is

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[6]See https://www.enotrans.org/etl-material/getting-to-the-route-of-it-the-role-of-governance-in-regional-transit/ for an overview of the MBTA's governance

London's integrated transport authority, responsible for the London Underground, London Overground, London Buses, Docklands Light Railway, and other transportation modes. TfL was created by the Greater London Authority Act of 1999, which empowers a Mayor of London. The majority of the Mayor's 17 billion annual budget is dedicated to TfL. Sadiq Khan, elected Mayor in 2016, highlighted as core campaign issues both the affordability of public transport and the development of new housing to accommodate an influx of residents. The Greater London Authority shares local government powers, including over land use, with 32 boroughs and the City of London. Decision-making is thus more centralized than in Greater Boston, but effective communication tools are still needed for engaging borough planning officers and other stakeholders, as well as the general public in wider consultation processes. In addition, for large projects such as Crossrail, engagement is needed with Government at the national level (e.g. Department for Transport [DfT] and HM Treasury) for funding and to secure powers to construct projects.

1.5 Dissertation structure

The following chapter in Part I outlines the theoretical foundations of this work and reviews past research on accessibility metrics, drawing partly from Stewart and Zegras (2016).

Part II covers two sets of stakeholder engagement workshops used as field tests for accessibility mapping tools. Chapters 3 and 4 are based on Stewart (2017). Chapter 3 reviews recent development of planning support systems (PSS) and connects literature about social learning with the design and development of new tools for co-creative transit planning. Chapter 4 discusses the evaluation of a dialog-based, accessibility-driven tool in participatory workshops. Specifically, four hypotheses are tested: that mutual learning occurs in the overall workshops; that learning structures of imagination and alignment, overall learning, and dialog quality are positively correlated; and that specific tool interactions correlate positively with individual imagination and group alignment. Chapter 5 extends this work with more formal experimental workshops that compare two versions of an interactive mapping tool – one showing accessibility results, and the other showing point-to-point travel time results. These results help build the case that specific aspects of the accessibility framing lead to substantially different engagement and dialog, which may be more conducive to stakeholder engagement favoring public transport projects. An important finding in both sets of workshops is that participant trust may be diminished if tools do not account for reliability and other constraints.

Part III responds to this finding by considering different versions of constrained accessibility. Chapter 6 reviews ways in which accessibility's value may be undervalued in project evaluation practice, but overestimated (e.g. by counting the total number of jobs, even if many of them might be only marginally relevant to most residents). The subsequent chapters address potential overestimation by including adjustments for reliability and matching constraints, which may reinforce each other and overlap with other layers of social exclusion. Chapter 7 uses the empirical case of connectivity between jobs and workers in London, and Chapter 8

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considers accessibility of healthcare centers to patients in Boston.

Part IV summarizes conclusions and recommendations for future research, connecting the preceding two parts of the dissertation. Findings from the workshops motivate the development of metrics that better represent experience, an important foundation for procedural equity. And adjusted accessibility metrics that distill complex spatial patterns into concise and meaningful representations of space, highlighting inequitable outcomes of transportation planning, may encourage a broader range of participants to make claims to just outcomes of transportation planning.

Chapter 2

Theoretical Underpinnings: Spatial Planning

Urban planners and engineers ostensibly commit themselves to serving the general public interest.[1] The public, however, is not a universal entity, but rather a myriad of constituent publics with particular interests (Faga (2006), Iveson (2011)). Governmentally-sanctioned urban planning serves to curate public discourses that build political will and guide intervention in shared spaces. Underpinning such discourses are techniques for crafting positivist characterizations of present conditions and uncertain futures. Planners balance both "sweeping vision" in shaping public narrative and "technocratic projection" through specific forms of expertise (Wachs, 2007, p. 367).

This chapter begins with an overview of (US-focused) urban planning theory. Even as urban/spatial planning practice has generally trended toward more collaborative models, much decision-making remains opaque in part because urban space is complex. Section 2.2 argues that this opaqueness is especially relevant for transport projects, because network effects may be counterintuitive, and because such effects have typically required abstraction from everyday user experience. Transport also makes the dynamics of centrality and the value of central places dependent on more than just central locations, as discussed in Section 2.3. Accessibility-based discussions may be a useful common ground for diverse actors to communicate about transport projects, and specific formulations of accessibility measures are detailed in Section 2.5.

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[1] The ASCE Code of Ethics reads, in part, "Engineers should be committed to improving the environment by adherence to the principles of sustainable development so as to enhance the quality of life of the general public." The AICP Code of Ethics begins "Our primary obligation is to serve the public interest."

2.1   Urban planning and power

Everyone has numbers that aren't quite the *numbers*

– Former MBTA General Manager Dr. Bev Scott
on public debates about transit performance

Broad visions, measurable objectives, and specific techniques all guide transportation planning and engineering (Meyer and Miller, 2001). Modern centralized transportation engineering emerged to design new highways, focusing on efficiency objectives and engineering analyses of flows while keeping broader social values largely insulated from debate (Banister, 2008). As public agencies gained responsibilities for maintaining and enhancing existing networks, economists' perspectives on cost effectiveness and allocation of shared resources grew more prevalent. Backlash against expert-led planning in the 1960s and 1970s forced values of representation and participation to be considered. The environmental justice movement that gained strength in the 1990s in the US, as well as advocacy about social exclusion in the UK, built on this progress to force the consideration of equitable transportation impacts, with related objectives and evaluative techniques.

Four sets of urban transport planning goals thus coexist today – centered on efficiency, effectiveness, participation, and justice. Deficient understandings of transit's dynamic spatial impacts limit each of them. Efficiency-focused infrastructure expansions may be overwhelmed by induced demand from land use changes. Benefit-cost or multi-criteria analyses may be seen as arbitrary, especially if the spatial distribution of impacts is unclear. Mandated participation is unlikely to foster meaningful empowerment, and confrontational grassroots groups are unlikely to achieve their demands, when spatial impacts are muddled. Regardless of the desired scope of transportation planning – whether the task at hand is persuasive (convincing a skeptical audience) or generative (creating project alternatives with diverse partners) – better spatial tools can be of value.

2.1.1   Theories of planning action

The need for better spatial modeling and communication tools is apparent through a slightly different framing of four guiding paradigms of planning and their associated discourses: technical-rational, advocacy, communicative, and collaborative planning. The primary promises and limitations of these approaches are discussed below, but first it should be noted that this framing roughly parallels the eight-rung ladder of citizen participation proposed by Arnstein (1969). Technical-rational planning requires little citizen participation but may include "informing" (rung three), while collaborative planning moves toward rungs six and above. Bailey and Grossardt (2010) argue that transportation planning in particular is subject to an "Arnstein Gap," a difference between what community stakeholders and transportation planning professionals think are the typical and the desired rungs, and that spatial tools to

support dialog can help close this gap.

Technical-rational planning

The technical experts have the numbers that are the numbers

Technical rationality, a paradigm not limited to transportation planning, involves the development of efficient, quantitative means to achieve specified ends (Schön, 1982). Starting with the predict-and-provide approach to provisioning highway capacity in the Interstate-building era, insulation of traffic engineering design from contentious politics was seen as desirable to prevent delays, cost overruns, political manipulation, and inefficiencies (Altshuler, 1965). This insulation is provided by scientific discourse and appearance of apolitical objectivity, which function to "render ordinary political life impotent through the threat of an incontestable nature" (Latour 2004, p. 10) in Culver (2015).

Despite these claims to incontestable objectivity, "planners and policy makers are strongly influenced by their political and institutional contexts" (Schön, 1982, p. 352). Flyvbjerg's (1998) case study of transportation planning in Aalborg describes how technical methods and rationality can be "subordinated to and used as an integral part of politics and power," belying claims to neutrality and instead suggesting that technical analyses are conducted "to rationalize and legitimate established attitudes and prior decisions" (p. 35). The privileging of scientific, positivist discourses over non-expert value-based judgments is a significant barrier to current efforts to move beyond the technical-rational paradigm and its associated "traffic logic" and "bias toward automobility" (Culver, 2015, p. 83).

Advocacy planning

The local experts have the numbers that are the numbers

Partly as a reaction against urban highways, and in conjunction with the activation of interest groups around diverse planning issues, movements to embed planning expertise within affected communities gained traction in the 1960s and 1970s (Schön (1982), Ross (2014)). These movements critiqued planning's processes and outcomes (Davidoff (1965), Fainstein and Fainstein (1974)) and helped secure legal mandates for participation (in US federal environmental legislation, for example).

Even with laws requiring public involvement, critics argue that "feedback from public to expert is highly constrained or nonexistent" in transportation planning; involvement can be caricatured as "decide-announce-defend" (Bailey and Grossardt, 2010, p. 68). Lefebvre (1991) offers similar criticisms of advocacy planning:

> When the interested parties – the 'users' – do not speak up, who can speak in their name or in their place? Certainly not some expert, some specialist of space

or of spokesmanship... The silence of the 'users' is indeed a problem – and it is the entire problem. The expert either works for himself alone or else he serves the interests of bureaucratic, financial, or political forces. If ever he were truly to confront these forces in the name of the interested parties, his fate would be sealed. (pp. 364-365)

Communicative Planning

The numbers we calculate and discuss together the *numbers*

Responding to critiques of tokenized public involvement, planning theorists began to emphasize communication and dialog ((Forester, 2001), Innes and Booher (2004)). This emphasis draws on Habermas's (1981) theory of communicative action to achieve agreement through dialog. On the one hand, communicative approaches "acknowledge the constraints of social structures and the power of interest groupings in shaping the information infrastructure within which planning outcomes are often determined" (Huxley and Yiftachel, 2000, p. 335).

On the other hand, Fainstein (2005) argues that communicative approaches do not adequately account for power: "If the powerful lose their advantages as a consequence of open communication, they are likely to either suppress unpleasant truths or to marginalize the tellers of them." (p. 125). Harvey (1997) notes, "Habermas has, in short, no conception of how spatio-temporalities and 'places' are produced and how that process is integral to the process of communicative action and of valuation" (p. 354), and Huxley and Yiftachel (2000) extend this criticism by commenting on the irony of Habermas's work being "taken up in the field of planning, a set of practices that above all else should be concerned with the production of space and place" (p. 336).

Collaborative, Co-Creative Planning

The numbers that we define together are the *numbers*

Better incorporating local knowledge and community expertise, especially as the complexity of urban space grows, is essential for envisioning future scenarios and improving project outcomes (Wachs (2007), Fischer (2000)). Emerging software tools for collaborative mapping can help transit agencies meet this requirement. These tools synthesize urban data, providing the possibility to spark new ways of representing and evaluating transport projects in relation to land use, equity, and the environment. Goodspeed (2013) asserts that "black box" models underlying traditional technical-rational planning are "beginning to converge" with more open and understandable "planning support systems" (PSS) (p. 65). More than mere data visualization or optimization tools, well-designed PSS can help participants engage in reflective dialog that reframes issues. Rather than optimizing for fixed objectives, participants may reflectively and collaboratively reconsider the objectives themselves, "double-loop learn-

ing" that encourages "new activities or disengaging from existing practices" (Payne et al. (2008), p. 88; see Goodspeed (2013), who also cites Argyris and Schn, 1978).

New digital data, network tools, and interactive software may enable co-creation, "direct engagement and interactions" (Gebauer et al., 2010, p. 512), by a broader range of experts and stakeholders. Such engagement may in turn expand the range of impacts considered in decision-making. Bailey and Grossardt (2010) call for structured public involvement using geospatial visualization technologies that should "elicit inter- and intrastakeholder dialog that otherwise is hard to encourage" and "help us "make sense together" (Forester 1989, 17), even if this dialog does not take the form of a classic consensus" (p. 70). They also argue that such structured public involvement can lead not only to more effective projects, but also to more just outcomes.

2.1.2   Power and planning experts

While these varied approaches to planning offer some promise of more efficient, effective, representative, and just outcomes, skeptics still question the role of power. Critical theorists have addressed the structural phenomena that prevent planning from truly achieving "change that [does] not primarily support the owners of capital (Castells 1977; Harvey 1978; Fainstein and Fainstein 1979)" (Fainstein, 2005, p. 124). Perhaps powerful interests will always ensure that their numbers that become *the* numbers. Flyvbjerg (1998) adopts this cynical view, noting how actors deploy both technical-rational and participatory approaches as tactics to advance powerful interests – "the tactical polyvalence of discourses." He draws on Foucault to describe "a dense and dynamic net of omnipresent relations" (p. 5) and interrogates "what 'governmental rationalities' are at work when those who govern govern" (p. 6). But this analysis largely glosses over the fundamentally spatial nature of planning.

Giddens (1984) offers the reminder that "discipline [in the Foucauldian sense] can only proceed via the manipulation of time and space" (p. 145). Critical geographers (e.g. Harvey, Soja) are well aware of the connection between space, capital, and power. Capitalism's "spatial fix" means its power, as well as its vulnerabilities, are embedded in space (Harvey, 1985). Planners must critically examine both power and "the role of planning as a state-related strategy in the creation and regulation of space" (Huxley and Yiftachel, 2000, p 339). Such examination is difficult partly because power and its spatial manifestations are pervasive yet masked:

> Dissimulation is necessarily part of any message from power. Thus space indeed 'speaks' – but it does not tell all. Above all, it prohibits... It is also a stake, the locus of projects and actions deployed as part of specific strategies (Lefebvre, 1991, pp. 142-143).

In other words, tools that seek to improve spatial understanding must be developed with cognizance of power relations fundamentally connected to space, and vice versa. Without this

awareness, even the most "open" planning tools run the risk of being subsumed by "empty ritual[s] of participation" (Arnstein, 1969, p. 217). Faga (2006, p. 110) also describes large public meetings as the "ritual of choice" despite the fact that they tend to produce "very little in the way of consensus or even exchange of useful information."

While such rituals may be empty in terms of productive outcomes for participants, they are rife with symbolic meaning. Repetition, role playing, stylization, order, staging, and social meaning in public involvement all contribute to inoculating bureaucratic actions against "reflective reconsideration" and endowing them "legitimacy and authenticity" (Goodsell, 1989, p. 162). Ritualistic public involvement is characterized by the intersection of highly proscribed relational spaces and highly constrained content spaces.

Participant attitudes can be classified along both procedural dimensions (e.g. trust in the process) and substantive dimensions (e.g. toward the merits of a specific project as measured by metrics accepted in the content space). Consider a two-way grid, of attitudes toward a project's substance and outcomes, and attitudes towards a public involvement process and the sponsoring agency's credibility. Attitudes must generally be strongly positive in both dimensions for participants to advocate for a project. Even if they appreciate a project on its merits, if they do not trust the implementing agency, they are unlikely to support a project and may even actively oppose it.

The layout of a room, tightly controlled agendas, and pre-generated materials all structure relational spaces; what is discussed, and how it is discussed, in turn affect and are affected by attitudes along the substantive dimension. For spatial planning, maps and cartographic representations of space tend to ground substantive debate, but these maps are prepared ahead of time by planners. Public feedback not already represented in these pre-made materials is easy to dismiss as off-topic. Such dismissals can lead to conflict and opposition along the procedural dimension. Considering local road projects in Minnesota, Quick et al. (2015) distill what participants dislike:

- Transportation system management innovations feel too risky or untested, or are not adequately explained.

- The "rules" or "the experts" dismiss the value of, or cannot accommodate, their knowledge and perspectives.

- They turn up to be heard, but are told their issue is not on the table for discussion, or that is it not negotiable.

- Participation feels like "window dressing" to legitimate an existing decision or to "sell" it.

- Important stakeholders are not aware of the meeting or are not in attendance.

- Engagement efforts are convened by people/institutions that have previously broken their trust, which takes a long time to restore.

(excerpts paraphrased and reordered)

The first two "dislikes" relate to constrained content spaces – not having the shared discourse to understand impacts, or disliking an intervention on its merits. The remaining items relate to procedural spaces. When materials and agendas are pre-made, participants have little latitude to address concerns that may be more relevant to them. If the "expert" planners have the power not only to dictate "*the* numbers," but also draw *the* maps unilaterally, meaningfully incorporating participants' spatial concerns is likely to be difficult or impossible.

Given the complexities of space, some level of simplification and abstraction is required. Expert cartography is often employed for this simplification, and traditional maps stress relationships based on proximity in Euclidean space. Forer (1978, p. 234) labels such space "absolute space"; along with its usual representation by technical-rational "expert" planners and architects, absolute space is "overwhelmingly static, easy to measure (by coordinate geometry) and a superb *lingua franca* among large groups of people through the medium of maps." But Giddens aruges that "in conditions of modernity... locales are thoroughly penetrated by and shaped in terms of social influences quite distant from them" (in Massey (1994, p. 6)). Transportation exists to create a divergence between physical distance and functional distance. With such divergence, it may be counterproductive for transport planning to rely solely on overly simplified, static maps of absolute space.

Actors in transportation planning are linked by "transportation system plans, designs, standards, measures, rhetorics, marketing, and decisions" (Sheller, 2015, p. 14), many of which are representations of networks that abstract from the wider urban context. The discourses shaping urban transportation include "agreed upon forms of 'objectivity' and rationality such as cost-benefit analyses, or 'level of service' measurement"; it is important to understand how actors use discourses, "frame transportation issues and shape decision-making contexts (Sheller, 2015, p. 14). While transport is fundamentally spatial, the complexity of network flows often leads discourse to be abstracted from space and familiar representations of place. This abstraction, reinforced in the typical narrative frames of transportation decision-making, is part of the "dissimulation" mentioned in subsection 2.1.2 and facilitates the misrecognition of power.

2.2   Flows, Places, and Space

> *When another driver makes a mistake, you need time to react. Give yourself this time by keeping a "space cushion" on all sides of your vehicle. This space cushion will give you room to brake or maneuver if you need the space.*
>
> – California Drivers Handbook

> *Our cities are being destroyed for [a] superstitious religious ritual: the worship of speed and empty space.*
>
> – Lewis Mumford

Cities can be understood as spaces of places and spaces of flows (Castells (1989), Prytherch and Cidell (2015)). Places connote bounded locations (i.e. specific points that can be represented with Cartesian coordinates), the traditional focus of land-use planning. Flows connote network complexities and exchange, the traditional subjects of transportation planning and telecommunications. The integration of land-use and transport planning is a long-sought goal. Such integration recognizes that places and flows are fundamentally interconnected.

While a place is often understood in terms of its boundaries, "what gives a place its specificity is not some long internalized history but the fact that it is constructed out of a particular constellation of social relations, meeting and weaving together at a particular locus" (Massey, 1994, p. 154). Places do not have single unique identities. They are full of conflict; "the specificity of place is continually reproduced, but it is not a specificity which results from some long, internalized history" (Massey, 1994, p. 155). Common spatial dynamics underlie spaces of flow and place, making "an integrative perspective on urban places of flow" apt (Prytherch and Cidell, 2015). Lefebvre (1991), noting that "coordination of... flows occurs within space," suggests three ways of reading space: as spatial practices, representations of space, and representational spaces. Abstraction is a potential pitfall for all three ways. According to Lefebvre, Lefebvre (1991, p. 308), abstract space "simultaneously embraces the hypertrophied analytic intellect; the state and bureaucratic raison d'etat; 'pure' knowledge; and the discourse of power."

Harvey (1990) extends Lefebvre's trialectic with three categories along a horizontal dimension that speaks to a Foucauldian reading of power: from accessibility and distanciation, through appropriation and use of space, to domination and control of space. Stewart (2010) populates the resulting nine cell matrix with the practices of transit agencies and riders. Here, I use Figure 2.2.1 to suggest how spatial planning might tie together these concepts.

In spatial planing, representations of space (e.g. maps) are the primary means of communicating substantive aspects of interventions. They shape perception and limit the discourses of planning. In techno-rational practice, experts use techniques of quantification to abstract from actual spatial practice (e.g. current driving patterns)to spatial representations (e.g. level-of-service at an intersection). Actors then appropriate these representations into their discourses and the procedural spaces of transport planning – representational spaces of hearings, meetings, and charrettes. Decision-makers can reshape technical discourse through rationalization (Flyvbjerg, 1998), and have the power to build and control the infrastructure that underlies spatial practice. Those not aligned with dominant public discourse are less able to shape infrastructure and are therefore limited in how they can use ("appropriate") infrastructure as their everyday spatial practice plays out over Euclidean/Cartesian space. In contrast, a collaborative approach to co-creation may include richer and more dynamic representations of space, avoiding the need, or at least the technical pretext for, selecting certain experiences as representative while excluding others.
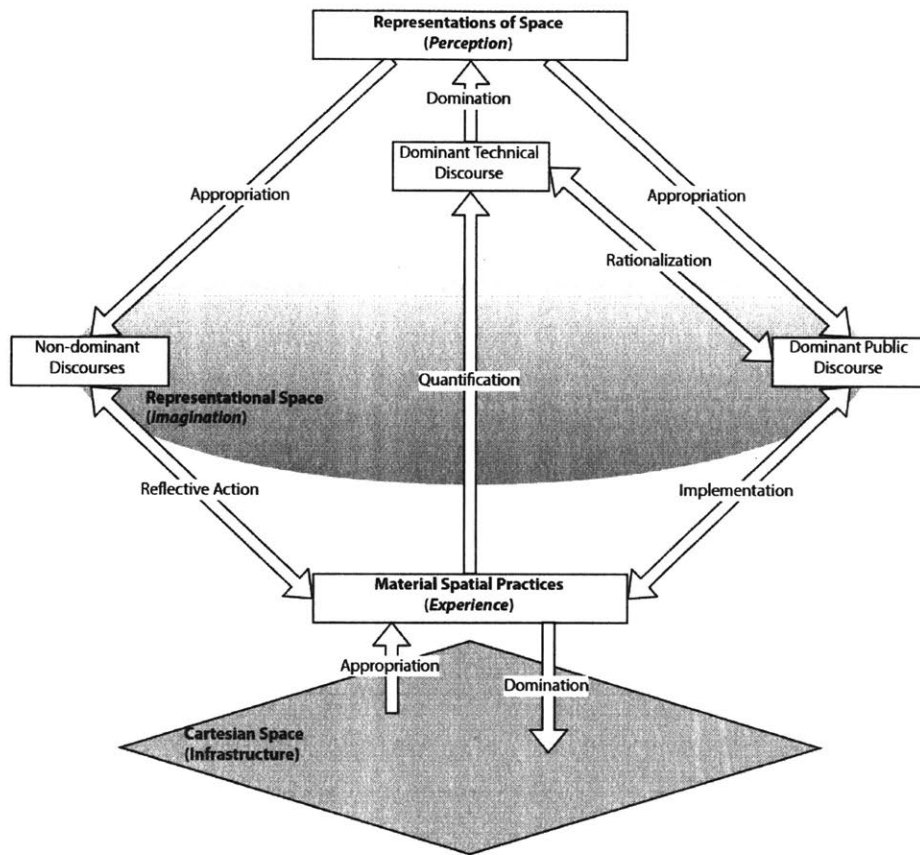
Figure 2.1: A framework to understand spatial planning

2.2.1 Abstract space

Some concrete examples of abstract spatial representations are in order.

Promotional materials for transport projects often rely on highly abstract representations of space. In Figure 2.2, a stylized transit network, with five proposed bus rapid transit corridors is superimposed on a blank map of Boston with generalized features[2]. Interchange points, the actual configuration of the road network, and population characteristics are all omitted from this representation of space. It is also paired with highly precise estimates of travel time; the 3.5 mile trip from Mattapan to Dudley Square will be reduced from 28.9 minutes to 19.2 minutes, a promised 33.7% improvement.

But questions should abound. From where in Mattapan? Under what conditions of congestion and crowding? With reliability equal to that of grade-separated rail, as implied by the

---

[2]I am not arguing that stylized transit diagrams are necessarily more abstract than strictly Cartesian maps. Diagrammatic representations in many cases may better align with passengers' perceptions and needs for information (e.g. which stations have step-free access) than strictly cartographic maps of tracks and stations. Raveau et al. (2011) and Guo (2011) both discuss the complex interplay between spatial practice and perceptions based on transit network diagrams.

5 Prime Corridors for BRT in Boston

SULLIVAN SQ

HARVARD

HAYMARKET

DUDLEY SQ

FOREST HILLS

MATTAPAN

READVILLE

LEGEND

Harvard to Dudley Corridor
Downtown to Dudley Corridor
Dudley to Mattapan Corridor
Sullivan to Longwood Corridor
Forest Hills to Readville Corridor
Red Line
Green Line
Orange Line
Blue Line
Commuter Line
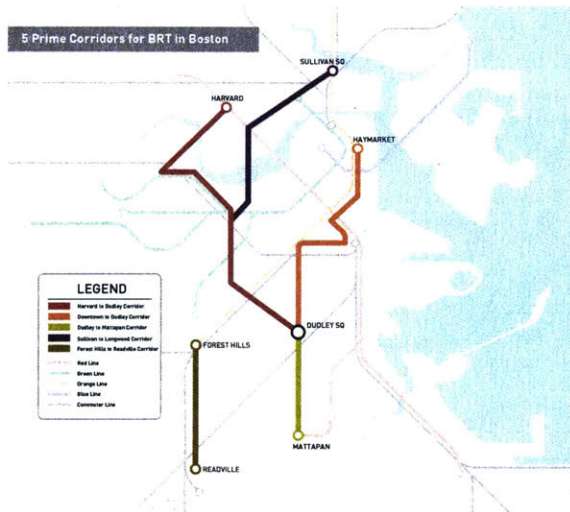
historic downtown streets could be comfortably repurposed for BRT. In the case of the Dudley to Downtown corridor, ITDP proposed two possible options for the downtown section—converting Devonshire to BRT only, or splitting the corridor into one-way pairs on Devonshire and Arch. This corridor can also either end at Haymarket, or in a one-way loop that runs past TD Garden and back to City Hall.

Dudley to Mattapan

This corridor would serve tremendous demand and potential along Blue Hill Avenue—one of the most heavily trafficked streets in the city—while improving connection between

culturally and historically important Mattapan and other hubs in the area. Community groups and the city are focusing on developing more retail and local business along this corridor, meaning that easy access and connection to the surrounding city will be crucial to its future success. And as other cities have experienced, a high-standard BRT corridor is a powerful tool for stimulating successful economic development, with well-designed stations and access to rapid transit anchoring investment in the neighborhood. Again, reducing time spent at overwhelmed bus stops increases speeds along this four-and-a-half-mile corridor.

Time Savings:
33.7% improvement

Dudley Square to Mattapan

28.9   19.2

Time Saved = 10 minutes

Routing Notes/Issues: The Study Group acknowledges challenges on this route. While Blue Hill Avenue has ample space for BRT, alternatives to the narrow section of Warren Street before it merges with Blue Hill are limited. Furthermore, a BRT route was previously proposed and withdrawn on Blue Hill Avenue, with concerns from the community (see Section V for more detail). With the very high existing demand that came up in ITDP's analysis, it would be a mistake to overlook the benefits BRT could hold for this important corridor of Boston. But any proposed BRT corridor must be driven by the communities' demand and vision for the neighborhoods involved.

Another compelling option with this proposal would be building it as one single corridor combined with the Dudley to Downtown corridor. This would create a single service traveling seven and a half miles from Mattapan to Downtown in about a half hour, without transfer, compared to the 52 minutes it takes now.

Readville to Forest Hills

This four-mile corridor would better connect Forest Hills Station to the Roslindale and Hyde Park neighborhoods, essentially extending the Orange Line to Readville. The overwhelming majority of the time saved is at bus stops, as peak times find Route 32 buses frequently packed and experiencing delays as large numbers of passengers wait to board. Downtown commuters using this busy corridor frequently must squeeze their way past fellow riders, and are no strangers to the disappointment of watching overloaded buses cruise past stops.

Time Savings:
27.8% improvement

Readville to Forest Hills

21.6   15.6

Time Saved = 6 minutes

Routing Notes/Issues: Similar to the Dudley to Downtown corridor, there is a narrow section of Hyde Park between River

and Madison streets, where there are a couple of options to make either BRT or mixed traffic one way, split between two parallel streets.

Harvard to Dudley

While the thought of traveling from Dudley Square to the heart of Cambridge in a half hour during highly congested peak hours is impressive, it's the improved connectivity for important academic and life science clusters that makes this corridor most exciting.

This option actually merges a few small potential corridors in the original 12 options to form one six-mile corridor with many benefits. The northernmost leg connects Harvard Square with Allston, it then comes down Commonwealth Avenue to the Fenway district, turning south through the Longwood Medical Area, one of the densest and fastest-developing areas of the city for job growth. The final segment ends up in Dudley Square, one of the busiest bus hubs in the city, which plays a central role in a number of these prime corridors due to overwhelming demand.

Residents of Greater Boston could gain many benefits from this corridor. For one, as Harvard expands into Lower Allston, the corridor could provide a better rapid transit option. The Longwood Medical Area has been looking to improve public transit to meet its rapid job growth. There are challenges to implementing the best route through Longwood, and this analysis found three options, each with pros and cons. But this corridor could create a fast transit option in the area, even adding an option for ambulance traffic, which could take advantage of a BRT lane, as happens in BRT corridors in other major cities. This route would also help to alleviate the gridlock that occurs before and after Red Sox games, affecting both attendees and regular traffic.

This is also the longest of the proposed corridors, and therefore shows the largest travel time savings with a 24-minute improvement. But it also offers the second-highest time savings by percentage. While current delays due to multiple bus stops and one-at-a-time boarding are significant, most of the benefit here would be relief from traffic congestion, thanks to dedicated lanes.

Time Savings:
42% improvement

Dudley Square to Harvard

56.8   32.9

Time Saved = 24 minutes
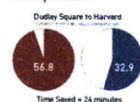
Figure 2.2: Time savings highlighted in the Better Rapid Transit for Greater Boston report (http://bostonbrt.org)

similar depiction of the bus corridors and the Red Line? At what cost? These questions are all glossed over by the abstract map paired with highly precise statistics, which exemplify techno-rational claims to objectivity and reality "of an incontestable nature" (Latour, cited above in 2.1.1).

Similar critiques could be made of Figure 2.3. A map of London, itself an abstract representation of complex spatial practices, is further obscured by a travel time that will be enabled because Crossrail was granted "powers." These figures make clear the overlap between signification (symbolism such as the abstract map), legitimization (a deference to objectivity and representative government), and domination (of political and economic institutions), using the terms of Giddens (1984). The interactions between between imagination and perception, which shape experience through the implementation of instrastructure projects, as suggested by the framework in Figure), is also at play.

Traditional maps and their extensions (e.g. in increasingly pervasive smartphone mapping

JOURNEY CALCULATOR

Crossrail Ltd is delivering a high frequency, high capacity service that will make travelling in the capital easier and quicker and will reduce crowding on London's transport network.

Find out how long your journey will take on the Elizabeth line.

Canary Wharf Station ⌄   Heathrow Central ⌄

Station details   View on map   Station details   View on map

Your journey will take
39min

Figure 2.3: Time savings highlighted on the Crossrail website (`http://crossrail.co.uk`)

applications) can intuitively and legibly represent space for users when speeds are uniform, networks have ubiquitous coverage and high connectivity, and users experience an internal locus of control. A fifteen-minute isochrone (line of constant travel time) or walkshed for a pedestrian tends to be nearly circular in areas with a dense, highly connected network of sidewalks. Similarly, given pervasive automobility, isochrones for car drivers tend to be somewhat circular, or at least largely contiguous, resembling "a continuous field" (Forer, 1978, p. 243). Figure 2.4 exemplifies this depiction of a continuous field – the entire state of Rhode Island is accessible from Providence within 70 minutes of driving.

Public transport networks, however, operate "through a set of punctiform interchanges between which interpolation is meaningless" (Forer, 1978, p. 244). Figure 2.5 shows an example of such discontinuities from New York. In the UK, a contour showing fifty minutes of travel time by rail from King's Cross Station intersects both Uxbridge (26 km away) and Cambridge (93 km away) (Marshall, 2001). These distortions, arising from differing speeds, frequencies, and timetables set by transport operators, diminish the concordance between traditional maps and how users imagine space. The distortions thus increase the cognitive burden inherent in using or deliberating about public transport, as compared to walking or driving. This increased cognitive burden may impede deliberations for transit projects, going beyond the factors identified by Casello et al. (2015) in hindering positive attitudes along the procedural dimension, in ways that are unique among transport projects generally. In short, the pitfalls of abstract space may be the most severe for communication about transit modes, the very modes for which deliberation and collaboration are most important (due to the economies of scale, the need for subsidies, etc.).
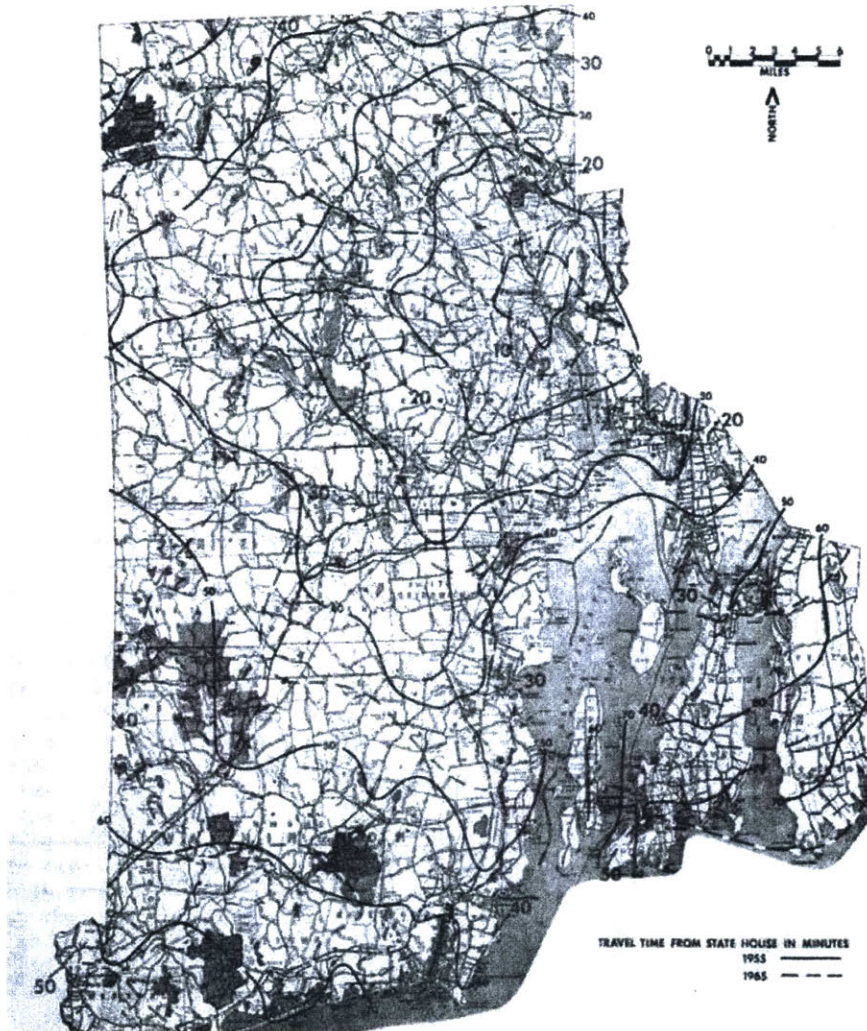
Figure 2.4: Isochrones for car travel from Providence, Rhode Island (Zimmer, 1974)
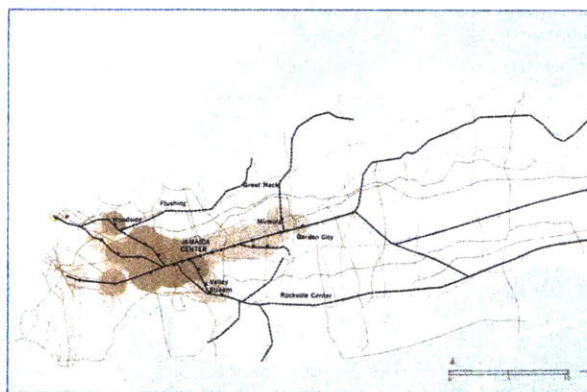
BY LONG ISLAND RAIL ROAD

At present speeds. Persons living within this area can reach Jamaica within 30 minutes total travel time (combination of auto and/or bus plus railroad). Over 180.000 white-collar workers live in this present commutershed (including some of those living within the area of a half-hour subway trip).

At future speeds. Persons living within this area will be able to reach Jamaica within 30 minutes total travel time (combination of auto and/or bus plus railroad). This enlargement of Jamaica's rail commutershed planned by the Metropolitan Transportation Authority will make it possible for many more workers, including those from areas of Nassau County, to have a short journey to work in Jamaica. But, in order to attract this growing labor force, office buildings must be located so that commuters can walk easily to them upon arrival by railroad in Jamaica.

Figure 2.5: Isochrones for train travel from Jamaica Center, New York (Towery and Zabarkes, 1968)

2.2.2 Differentiated/plastic space

One of Lefebvre's antidotes to spatial abstraction is an embrace of differentiated space. Individuals' spatial practices are tied to their abilities, and these unique characteristics can be the basis for claims on spatial representations. Urban spaces, as practiced by individuals and shaped by transportation, are "plastic" (Forer (1978), Ahmed and Miller (2007)).

Consider Figure 2.6, which represents travel from Downtown Crossing in Boston. Absolute or abstract conceptions of space privilege Euclidean distance; places within a 5-kilometer radius of this location (as shown by the circle), for example, might be considered reasonably proximate.

The 40-minute isochrone (from Downtown Crossing, assuming a random departure time during the morning peak, by walking and scheduled MBTA transit services) shows a different set of areas that might be considered proximate. The discrepancy between the two highlights how transportation distorts functional distance, making space plastic. Though Grove Hall in Roxbury is within five kilometers of Downtown Crossing, its distance from rapid transit options (the Red and Orange Lines) makes it unreachable within 40 minutes. Though Quincy is twice as far away, it is reachable within 40 minutes – an effect of fast trains similar to the Uxbridge/Cambridge example above.

One might assume that shifting the origin of Figure 2.6 closer to Roxbury would make it more easily reachable. Figure 2.7 shows results for an origin slightly closer, Copley Square. But this shift makes Roxbury and Dorchester even harder to reach, as fast, frequent Red Line service is less proximate. Maps that show only Euclidean distances can obscure such non-intuitive results.

Change in both the "small time" of daily variability and the "big time" of history and multi-year changes in infrastructure (Forer, 1978) are important to consider here.

Day-to-day variability introduces one level of plasticity. Figure 2.8 shows the same 40-minute isochrone from Copley Square, along with 40-minute isochrones based on actual MBTA operations for ten days in October, 2016 (see Chapter 8 for details and extensions of these calculations). The isochrones representing actually operated service are further shrunk, especially in areas between rail lines like Roxbury. An embrace of differentiated space recognizes this plasticity, that individuals' lived spatial practice and mental maps may differ substantially from averages based on scheduled service, depending on their modes, times, and days of travel. It may of course be impractical to fragment understanding into infinite individual maps varying by behavior, preference, and ability – what Forer (1978) labels "behavioral space." At the other extreme, abstract/absolute space relies on *the* singular (base)map, built on Euclidean relations that represent Copley and Roxbury as closer together than Copley and Malden, even though the latter pair is functionally closer together based on transit service. Differentiated/plastic space strikes a balance, accepting "an objective but changing metric suitable for aggregate considerations" (Forer, 1978, p. 235).

Plastic spaces are also shaped over history. The hole in the Downtown Crossing isochrone at Roxbury (in Figure 2.6) likely emerged when the Orange Line was relocated from Dudley Square to its current alignment in the late 1980s, a point argued by advocacy groups in Roxbury (Stewart, 2010). But without this relocation, the concavity in the isochrone from Copley Square (in Figure 2.7) would be much more pronounced, further reducing accessibility to the large cluster of jobs in the Back Bay (see Figure 2.9). Giddens's (1984) reminder, that "spatiality, sociality, and historicality are mutually constitutive" (p. 18), is worth repeating here.

Looking forward, improvements to the mobility system might expand these isochrones. But if gentrification occurs in the land market, current residents may be displaced to less accessible locations, denying them increased access despite the improved accessibility of their (former) homes. Here, the distinction between access (a function of an individual's attributes and location) and accessibility (a function largely of location) is important.
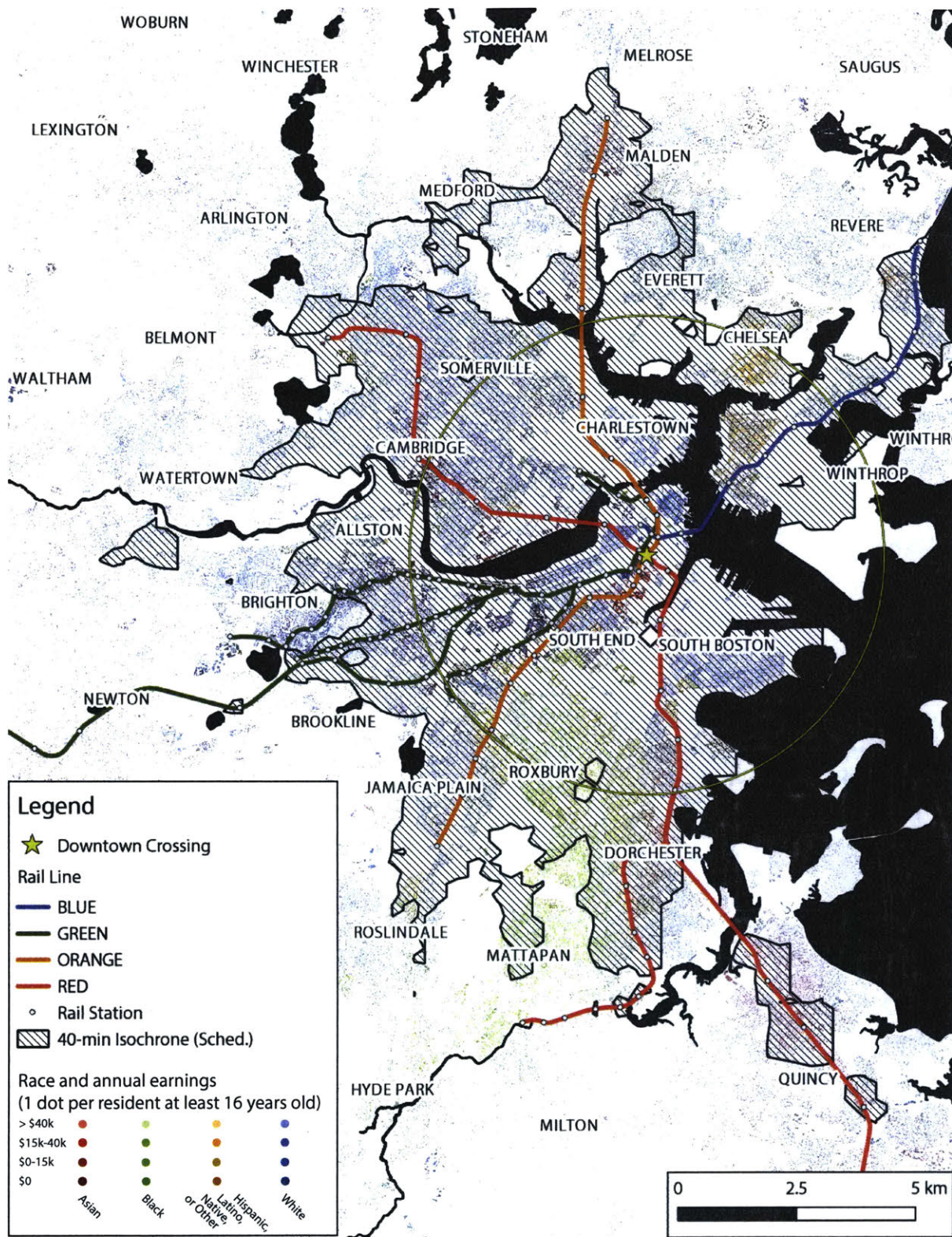
Figure 2.6: 40-minute isochrone and 5-km circular buffer from Downtown Crossing, Boston (Basemap data: US Census Bureau [Census 2010, ACS 5-year datasets], MassGIS)
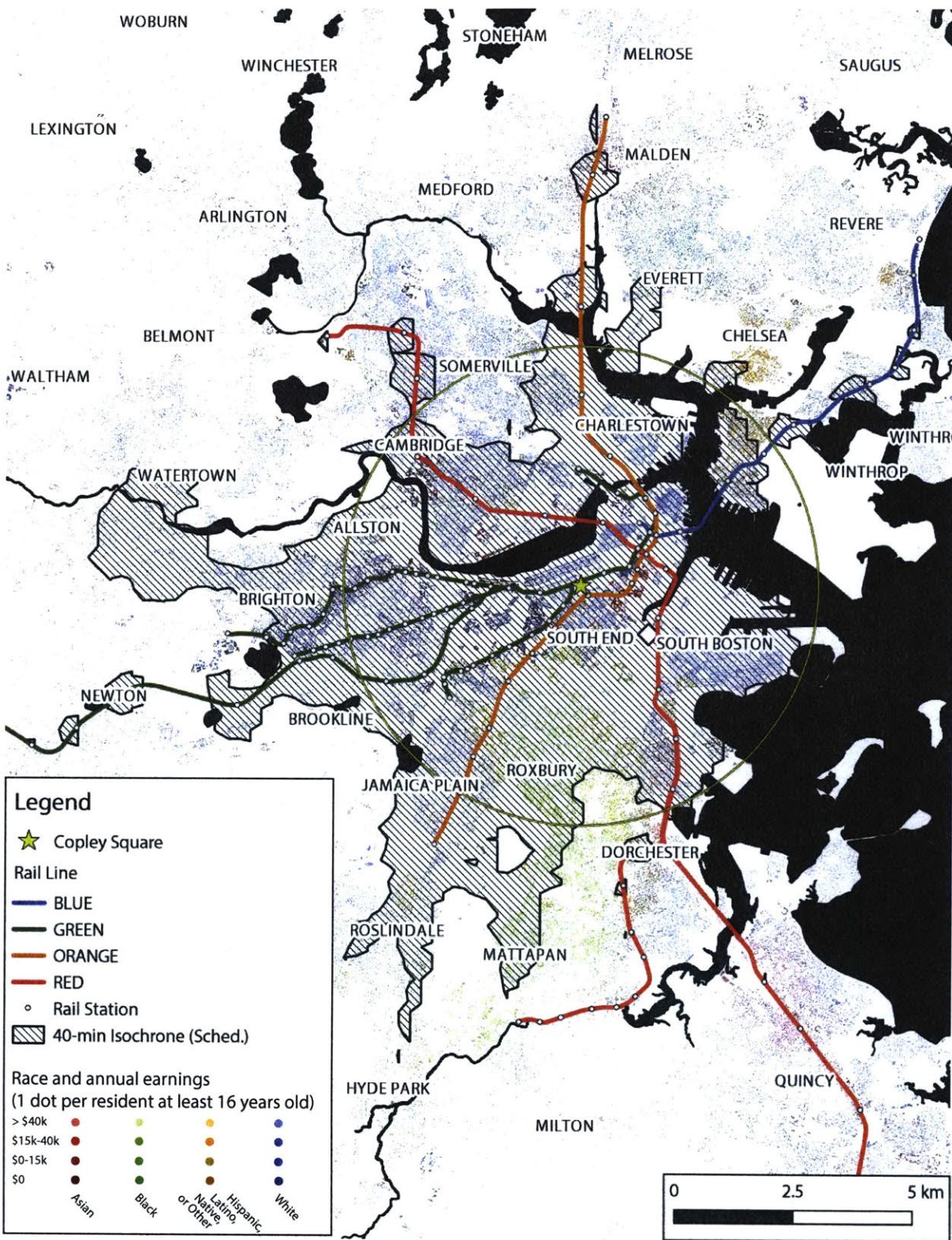
Figure 2.7: 40-minute isochrone and 5-km circular buffer from Copley Square, Boston (Basemap data: US Census Bureau [Census 2010, ACS 5-year datasets], MassGIS)

Legend

⭐ Copley Square

Rail Line
— BLUE
— GREEN
— ORANGE
— RED
∘ Rail Station
▨ 40-min Isochrone (Sched.)

Race and annual earnings
(1 dot per resident at least 16 years old)
> $40k
$15k-40k
$0-15k
$0
Asian   Black   Hispanic, Latino, Native, or Other   White
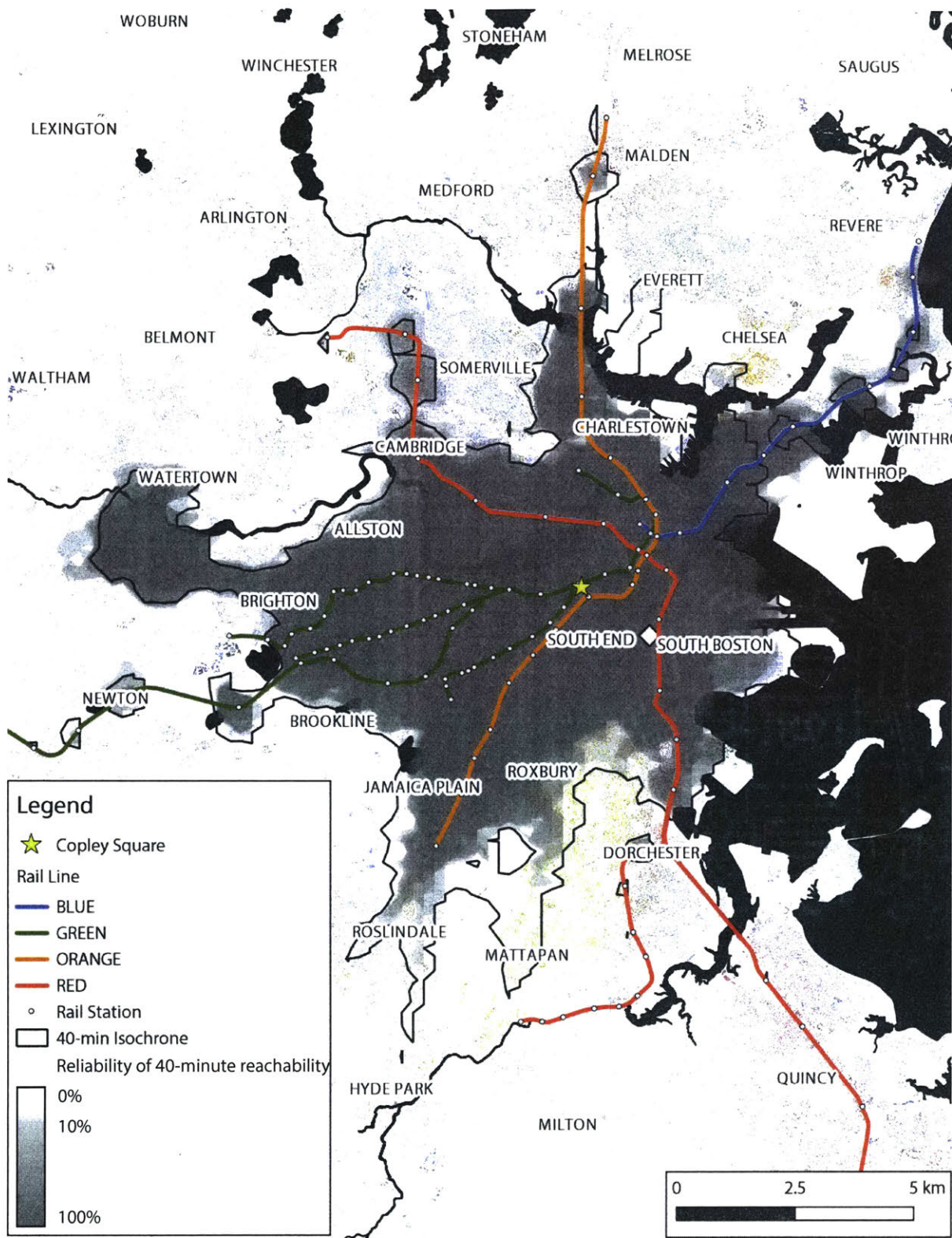
Figure 2.8: 40-minute isochrones from Copley Square for ten weekdays in late October 2016. (Basemap data: US Census Bureau (Census 2010, ACS 5-year datasets), MassGIS)
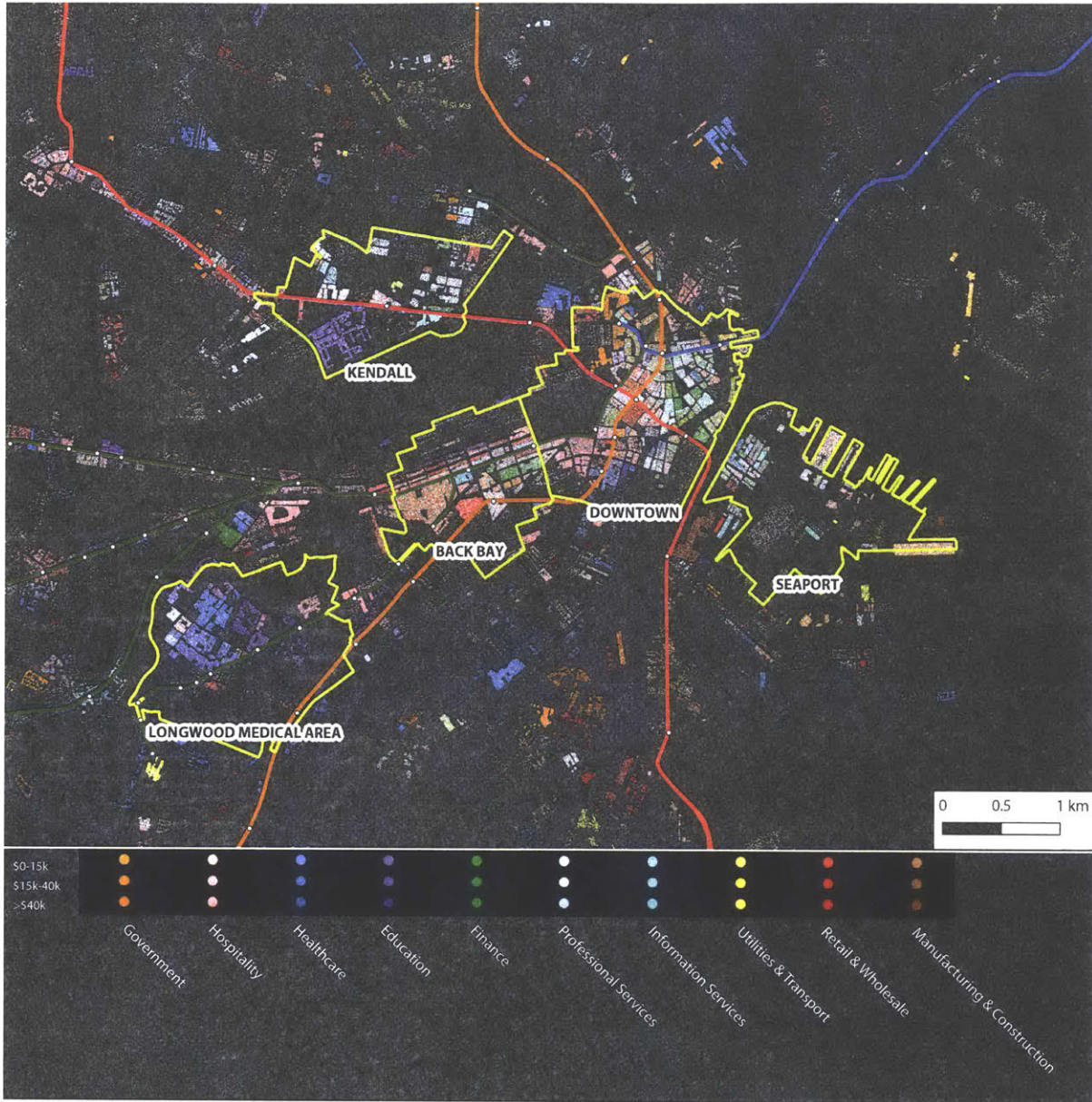
Figure 2.9: Job clusters in Greater Boston (Data: Census Bureau (Data: LEHD LODES 2014)

2.3   Centrality, dislocation, and capital

It's the cycle of the city. I need to pay my staff a decent wage so they can live in London. It's a pattern. You can ride the wave or get off the beach.
– Vanessa Garrett, owner of Food for Thought, a London restaurant that closed in
2015 after four decades in Covent Garden

Cataclysmic money pours into an area in concentrated form, producing drastic changes... [Moneys] behave not like irrigation systems, bringing life-giving streams to feed steady, continual growth. Instead, they behave like manifestations of malevolent climates beyond the control of man – affording either searing droughts or torrential, eroding floods.

– Jane Jacobs
The Death and Life of Great American Cities

The dialectic of centrality-peripherality spans urban spatial scales. Moving beyond abstract space requires a recognition that centrality is not merely locational, but it is "a social product that internalizes moments of gathering-inclusion and dispersal-exclusion. Privileged products, people, and symbols are brought together at the same time that dissident or undesirable elements are peripheralized" (Addie, 2015, p. 190). Consider again Figure 2.8. The basemap of this figure shows working-age residents by race and wage levels. While the largely black neighborhoods of Roxbury, Dorchester, and Mattapan are proximate in a narrow locational sense to the civic institutions and centers of prestige capital and economic power in Downtown Boston and the Back Bay (see Figure 2.9), they are distant from a wider spatial perspective. A "social geometry of power and signification" (Massey, 1994, p. 3) is at play. Massey (1994) continues:

> White-collar middle-income professional and managerial strata...have a very particular geography. It is a geography of both concentration and privilege... The social power of these groups (for instance, their bargaining power within the labor market) gives them a power of choice of location, which may be fed through the perception of their preferences by the companies which seek their labor power. And they exercise that power overwhelmingly to avoid the physical and social environment of decline (perhaps the only exception, though it still replicates this pattern at a much smaller scale, is that of gentrification). But what this means is that these groups use their social power to reinforce their privilege through location. And that in turn exacerbates the unevenness of uneven development." (p. 328)

The centrality-peripherality dialectic (again, not in a simple locational sense) epitomizes uneven development. Lefebvre (1991, p. 332) elaborates on centrality and planners' roles in supporting it: "Centrality now aspires to be total. It thus lays claim, implicitly or explicitly, to a superior political rationality... It falls to the agents of the technostructure – to the planners – to provide a justification for this claim." Planners' justifications for certain forms of centrality allow privileged groups to reinforce their privilege by locating in certain areas. And because urban space is scarce, disadvantaged groups will find disadvantage reinforced through low-accessibility locations. This tendency is recognized in both basic theory about urban land markets, and in more recent literature about social exclusion:

> Social exclusion...is a concept that emphasizes the importance of a complex set of inter-related social processes (not just wealth creation) and which concentrates on the relational; that is the relationships of power between individuals, institutions and others... In terms of social exclusion and transport, it is not simply the provision and use of the transport system but also participation in the processes which determine the operation and management of the system that is important. (Hodgson and Turner, 2003, p. 272)

Spatial and social exclusion overlap: "Those who tend to be least accessible to jobs, health care, and other important destinations also wield the least political clout" (Cervero et al. (1999, p. 1277); see also Altshuler (1979) and Pirie (1981)). While some recommendations to address social exclusion have been put into place (e.g. Social Exclusion Unit (2003)), these have been largely localized efforts (Preston and Rajé, 2007). But siloing solutions falls prey to the disjointedness of abstract space; an integrative perspective is needed.

2.4 Accessibility: integrating transport, land use, and identity

Transportation planning based on principles of justice requires, first and foremost, the identification of population groups experiencing an accessibility shortage

– Karel Martens
Transport Justice

Concluding his seminal *The Constitution of Society*, Giddens (1984) writes, "Space is not an empty dimension along which social groupings become structured, but has to be considered in terms of its involvement in the constitution of systems of interaction." (p. 368). Accessibility and connectivity recognize this reality, that "localities can in a sense be present in one another, both inside and outside at the same time" (Massey, 1994, p. 7). The accessibility lens is not just the inverse of the travel time lens; it can help open new spaces of representation.

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Accessibility planning can complement traditional mobility planning along multiple dimensions. See the table below (and the comparisons in Banister (2008)).

	Mobility Planning	Accessibility Planning
Goal	Precise predictions	Informative scenarios
Benefits	Realized (travel time, emissions)	Potential (option value, agglomeration)
Iteration	Within models (dynamic assignment)	Of analysis (scenario exploration)
Scope	Supply and Demand	Supply

2.4.1 As common ground for collaboration and equity

Locational accessibility metrics are inherently geographical, potentially enabling collaboration across disciplines and interest groups. The language of accessibility can be a common ground for technical experts of different backgrounds (e.g. land use and transport planners), and for residents of different areas of a region. As Miller (1999) writes, "The spatial distribution of accessibility, particularly changes in accessibility, can tell the planner or policy analyst directly who are the 'winners' and 'losers' in a given scenario" (p. 2). For new public transit projects in complex networks, beneficiaries may be distant from the project itself. Such remote beneficiaries would be unlikely to have supportive substantive attitudes unless non-intuitive benefits can be clearly communicated.

Furthermore, the focus on potential for interaction, rather than speeding interactions that already occur, can better address issues of social exclusion for areas where current travel is limited because of poor transport service. Accessibility planning avoids the biases inherent in the use of willingness-to-pay, existing trip rates, and value of time (Lucas et al. (2015), Nahmias-Biran and Shiftan (2016), Martens (2017)). The ability to identify winners and losers, or the incidence of benefits and costs, is fundamental to equity analysis. Accessibility measures have been proposed as the basis for equity evaluations using Gini indices (Welch and Mishra (2013), Lucas et al. (2015)) and other indicators (Manaugh and El-Geneidy (2012), Golub and Martens (2014), Martens (2017)). These metrics are thus appealing both as informative tools for achieving more equitable outcomes, and – if formulated and applied transparently, engagingly, and widely – more equitable processes with more positive procedural attitudes.

This last condition can be a big "if." Lucas (2012) offers a cautionary tale in the case of the UK Department for Transprot (DfT):

> The DfT's 'black box' approach prevailed over the more qualitative and grounded approach to local problem identification envisaged by the [Social Exclusion Unit]... It diverted attention away from the actual needs of disadvantaged populatons and tended towards an overemphasis on 'fixing' the public transport system. This was in contravention of key theories of social exclusion which highlight the complex and multidimensional nature of the phenomenon and suggest the need for multi-

level, multifaceted solutions which include the participation and involvement of affected individuals and communities. (p. 232).

Both substantive equity and procedural equity are important goals. Accessibility analysis cannot achieve its potential for effecting equity if it merely takes the place of other "black box" means of translating experience (spatial practice) into abstract, quantified representations of space (see Figure 2.2.1). Instead, as suggested in Figure 2.10, accessibility should be embraced as a shared, representational space through which individuals can communicate about their unique spatial practices with land use and transport planners.
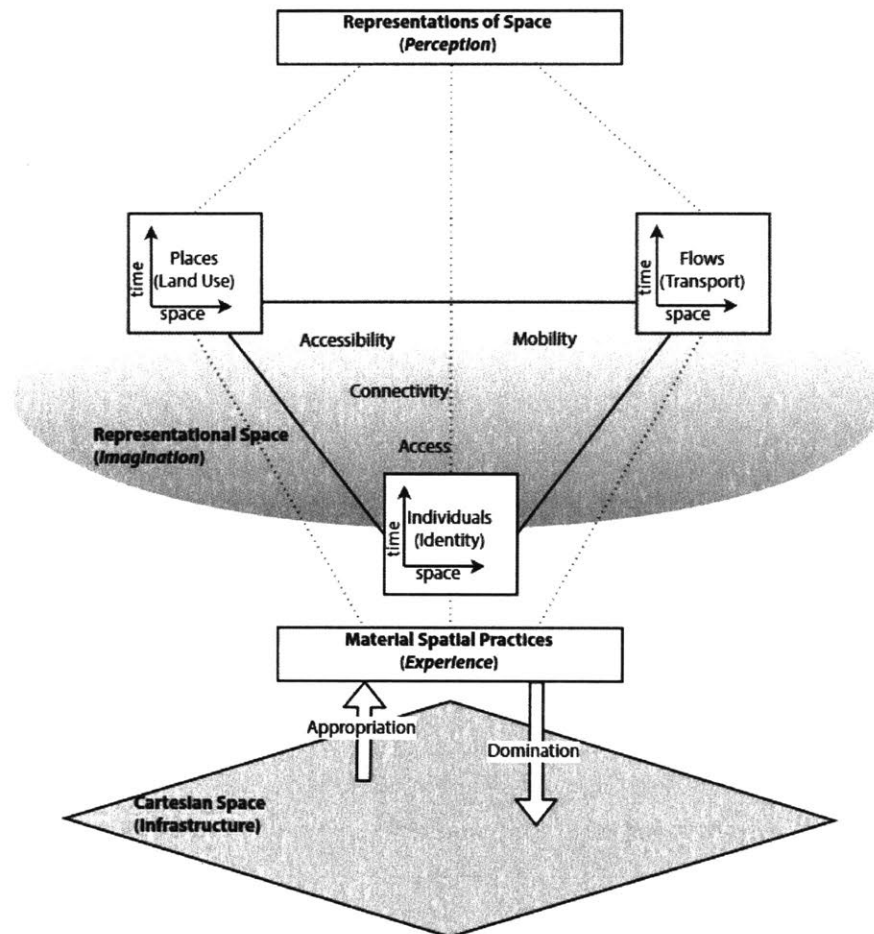
Figure 2.10: Accessibility in the framework of spatial planning

2.4.2   As a means toward wider economic benefits

The benefits of transportation investments generally extend beyond individual travel time savings. The connectivity afforded by transport links enables higher effective densities, the

clustering of firms within short distances or travel times of each other. For certain industries (e.g. business services), higher effective densities have been shown to translate into higher productivity (Graham, 2007a). In addition, improved accessibility of a cluster can expand the size of a citys employment market, which also correlates positively with productivity (Venables, 2007). Alstadt et al. (2012) emphasize the growing need to be able to "consider both industry detail and forms of accessibility in order to calculate accurately the relative impact of specific project proposals" (p. 154). Such considerations are the focus of Chapter 7.

2.4.3 As basic human welfare

In addition to being a means toward wider economic benefit ends, accessibility can be framed as an end in itself. This framing relates to the idea of transport as a derived demand; rarely do we desire mobility for itself, rather we desire the ultimate access that mobility enables. Sclar and Lönnroth (2014) assert, "Few dispute the fact that the goal of expanding urban transport is to facilitate improved urban access" (p. 1). Metz (2008) explicitly calls for transport project appraisal to flip the travel time savings focus to an accessibility focus. Zegras (2011) argues that accessibility forms the core purpose of "sustainable mobility," where individuals' access (greater choices to different opportunities) represents basic human welfare and well-being.

2.4.4 As a policy objective

Leading US metropolitan planning organizations have started to adopt accessibility-based policies for equity analyses (Handy, 2017). Grengs (2015) cites the examples of the San Francisco MTC and the Mid-Ohio RPC, and Merlin (2017) notes examples from the Puget Sound region. Accessibility metrics have also been mentioned in federal transportation policy:

> The Administration included funding for a $70 million Connectivity Pilot Study in the GROW AMERICA Act, the results of which could eventually be used to inform a possible national connectivity in transportation measure. Such a national measure would allow investment in the areas and projects that are doing the most to promote economic mobility by improving access to jobs, education, and essential services through transportation infrastructure. (USDOT, 2015)

In the UK, accessibility planning gained some traction (with Accession being a notable tool), but it tends toward "local transport solutions rather than a broader set of integrated land-use and service delivery policies to improve access to jobs, training, healthcare, and so on" (Lucas, 2012, p. 233).

2.5 Accessibility metrics

Translating policy goals into actionable indicators requires the formulation of specific metrics. Almost all accessibility metrics have two elements – "a transportation (or resistance or impedance) element and an activity (or motivation or attraction) element." (Handy and Niemeier, 1997, p. 1176)

2.5.1 Utility-based accessibility metrics

Koenig (1980) describes a behavioral utility-based connectivity measure, the utility gained from the activity destination (a random variable) minus the cost of accessing it. Also drawing on random utility, Ben-Akiva and Lerman argue for the denominator of the multinomial logit model (the logsum), "a summary measure indicating the desirability of the full choice set (Small, 1992). The specified utility function includes variables that represent the attributes of each choice, reflecting the attractiveness of the destination and the travel impedance that must be overcome to reach the destination, and the socioeconomic characteristics of the individual or household, reflecting individual tastes and preferences" (Handy and Niemeier, 1997, p. 1178). Dong et al. (2006) proposes an activity-based accessibility measure that is an individual's expected maximum utility among available activity schedules, given a fixed residential location, which relies on a day-activity-schedule model system with extensive data requirements.

While these measures may be economically rigorous, collecting adequate data, interpreting and communicating results, and comparing across contexts is a challenge (Handy and Niemeier (1997), Geurs and Van Wee (2004)). (Van Wee et al., 2001, p. 12) raises a number of additional complications regarding utility-based measures: "the value of having multiple options is ignored, as is the 'love of variety in consumption'"; "using willingness to pay to calculate utility is disputed,... as is the assumption on the link between income and utility"; and "due to autocorrelation the IIA-assumption might be violated in the case of destination choice."

2.5.2 Space-time accessibility metrics

Building on the work of Hägerstrand (1970), a range of space-time accessibility metrics have been proposed (Kwan (1998), Miller (1999)). These metrics can be based on the potential path area coverable by people given fixed spatio-temporal constraints, on the volume of a space-time prism, or on an attractiveness function that tallies amount of time able to be spent at any given destination. Neutens et al. (2012) shows high variation in accessibility to Belgian government services between days within a week. Such detailed measures are often better tailored to facility planning around a well-understood set of schedules than to transportation planning.

For these reasons, and recognizing that the complexity and data requirements of utility and space-time measures may detract substantially from co-creative and collaborative planning, more straightforward integral measures are the primary focus of this dissertation.

2.5.3 Integral accessibility metrics

An integral measure of accessibility from a given origin sums, across all possible destinations, an attractiveness function multiplied by an impedance function (generally monotonically decreasing, as discussed below). Though inputs are often aggregated into zones, they can also be disaggregate point features (Hanson and Schwab (1987), Kwan (1998)).

The attractiveness function can be a count of opportunities (e.g. jobs, schools, hospital beds) or a function of trip-makers' awareness, hours of operation, opportunity availability (e.g. Cascetta et al. (2016)), or other factors.

For a set of individuals or origin zones ($i = 1...n$) and a set of destination opportunities or zones ($j = 1...m$), an accessibility metric a_i can be calculated for each origin as:

$$a_i(D, M, T, \tau) = \sum_{j=1}^{m} q_j(D) f(t_{ij}(M, T))$$

where:

D is the selected destination type (e.g. jobs, healthcare facilities, potential employees available, which may vary according to T)

M is the mode of travel (e.g. auto, transit)

T is a time window for the trip (e.g. peak, off-peak), which implies a certain pattern of service offered, congestion delays, etc.

τ is the cutoff time if a sharp cutoff measure is used (e.g. binary cutoff), see below.

$q_j(D)$ is the attractiveness or number of opportunities of type D in zone j

$t_{ij}(M, T)$ is a representative (e.g. minimum, maximum, median, or mean) time or generalized cost to travel from zone i to zone j by mode M in time period T

$f(t)$ is an attractiveness decay function, generally returning decreasing values as the time or generalized cost argument t increases

A cumulative plot of the number of reachable opportunities versus t_{ij} is a graphical representation the accessibility of a given origin i.

Impedance functions

The impedance function, $f(t_{ij})$, reflects to what extent additional travel time/cost diminishes the value of the destination opportunity $d_j(D)$. Also known as distance-substitution functions, decay functions, or friction functions, these functions return discounted attractiveness values "equivalent" to attractiveness if the destination activities considered were all collapsed into one location at the trip origin (Black and Conroy (1977), Ducas (2011)). Example impedance functions are illustrated in Figure 2.11 and discussed below.

The argument for the impedance function, t_{ij} can be pure travel time, or a generalized cost with weighted components. It can represent an ideal travel time; for roads, this time can be based on free-flow speeds, and for transit, it can be based on the explicit schedules for trips or average frequencies. Chapter 6 discusses adjustments for non-ideal travel times. Monetary cost and affordability can also be incorporated in a generalized cost argument (see Venter (2016)).
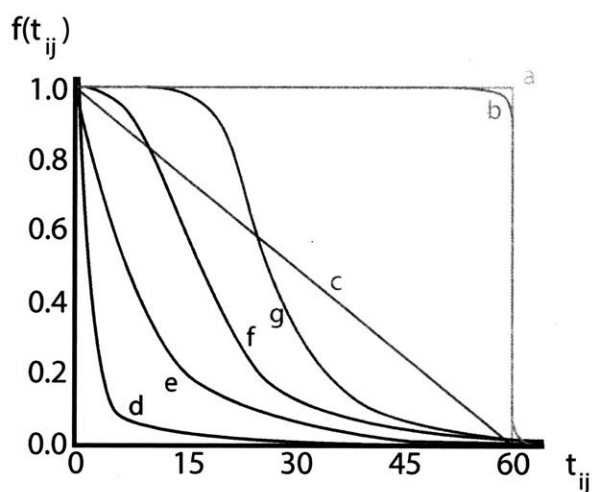
Figure 2.11: Example impedance functions (based on Kwan (1998))

At one extreme, someone might value equally all opportunities within a cutoff value; for example, in the binary function of Figure 2.11(a), all opportunities within the one-hour cutoff ($\tau = 60$) are weighted by a factor of 1, while all opportunities beyond are weighted with a factor of 0.

Kwan (1998) and others classify such measures, with a cutoff parameter specified, as cumulative-opportunity measures. At the other extreme, someone might value opportunities at the origin very highly, with steep discounts for opportunities more than a few minutes away (e.g. Figure 2.11 (d)). Such gravity-type measures[3] include other parameters, which are generally

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[3]Gravity measures are analogous to gravitational force decreasing with the square of the distance between two bodies in Newton's universal law of gravitation. This analogy goes back at least to William Reilly's 1931 *Law of Retail Gravitation*.

estimated based on regional trip-length distributions.

Accessibility measures derived from cumulative-opportunity and gravity-type impedance functions tend to be positively correlated. Testing a range of functional forms and parameters in the case of Cleveland, Kwan (1998) finds generally high correlations, with the exception of the binary-type functions with cutoffs of at least $\tau = 40$. Even the correlation between a function with $\tau = 30$ and $\tau = 40$ is only 0.549, highlighting the theoretical limitations of binary cutoff measures.

Cumulative-opportunity type

Binary cutoff

$$f(t) = \begin{cases} 1 \text{ if } t \leq \tau \\ 0 \text{ otherwise} \end{cases}$$

Accessibility metrics of this form are sometimes called isochrone measures. Figure 2.11 (a) is an example of a binary cutoff impedance function with a threshold parameter, τ, of 60 minutes. This function has been used to construct various indices (e.g. Wachs and Kumagai (1973)).

The main advantage of such functions is ease of interpretation and communication; the units of the resulting accessibility measure (e.g. number of jobs) are easily understood. The theoretical standing of such measures is questionable; few would argue that an opportunity 5 minutes away is just as valuable as one 55 minutes away. There are also boundary issues that may be significant. If a threshold of 30 minutes is selected, for example, then jobs that are 31 minutes away from a given zone would not influence the accessibility score of that zone, even though in reality they could likely benefit residents of that zone.

Logistic rolloff

$$f(t) = 1/(1 + e^{\rho(t-\tau)})$$

One way to overcome the boundary issue described above is to use a smoothing function, such as a logistic rolloff. Figure 2.11 (b) shows such a function, with $\rho = 2$ and $\tau = 60$, leading to a smoothed drop-off between about 58 and 62 minutes.

Negative linear

$$f(t) = 1 - t/\tau$$

Black and Conroy (1977) use a negative linear function (Figure 2.11 (c)), and show that accessibility measures using this functional form are equivalent to taking the area under a

cumulative plot of accessibility. Recognizing the decreasing value of more distant opportunities, this type of measure is a bridge to gravity-type measures.

Gravity type

While distance-decay or gravity-type metrics avoid the cutoff problems of binary cumulative opportunity measures, they are also dependent on behavioral data to estimate functional parameters (e.g. α, β, etc., as described below) and do not have units that are as as meaningful or as easily communicated. Interpretation may be best left to "number of opportunities easily reachable," with "easily" requiring further explanation.

Levine et al. (2012, p. 161) raises an important theoretical limitation to using such estimation procedures for accessibility measures:

> "Willingness to travel is a function of the opportunities available. Regions in which many destinations were close by and few far away would presumably demonstrate greater reticence to travel (and, thus, a higher value for β) than those with few nearby destinations and many farther away... Using region-specific parameters would have the effect of giving accessibility credit to a region in which people readily take long trips. But if their propensity to take long trips is a function in part of lack of nearby destinations, then the region-specific parameter would tend to overestimate the accessibility of these places compared to others where long-distance trips were less necessary."

Inverse power

$$f(t) = t^{-\alpha}$$

Figure 2.11 (d) shows the classic form of impedance function proposed by Hansen (1959) ($\alpha_{employment} = 2.2$, $\alpha_{shopping} = 3.0$). It is also the form specified by DfT (2014) for calculating effective density of jobs[4], with $\alpha_{manufacturing} = 1.097$, $\alpha_{consumer\,services} = 1.818$, and $\alpha_{producer\,services} = 1.746$). Shen and Zhao (2017) uses this form for regional high-speed rail travel ($\alpha = 1$).

Negative exponential

$$f(t) = e^{-\beta t}$$

Figure 2.11 (e) shows a typical negative exponential impedance function.

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[4]Effective density denotes the number of entities that can be accessed within a given time or generalized cost, as opposed to density, which connotes the number of entities within a fixed distance. It is a specific case of accessibility, where D is of the same class as the origin population.

To rank the accessibility of different metropolitan regions, Owen and Levinson (2014) apply this form of impedance to accessibility values aggregated into 10 minute bins, with $\beta = 0.08$.

Ingram (1971) uses a modified negative exponential function, resembling the normal (Gaussian) distribution: $f(t_{ij}) = e^{-(1/\nu)t_{ij}^2}$ (see Figure 2.11 (f)). Levinson and Kumar (1994) use a similarly modified function: $f(t) = e^{at+b\sqrt{t}+ct^2+d}$

Gamma

$$f(t_{ij}) = \gamma t_{ij}^{-\alpha} e^{-\beta t_{ij}}$$

Figure 2.11 (g) shows a gamma function, also called a Tanner function (see Martínez and Viegas (2013)), modified with a "shelf" of indifference up to a cutoff, as proposed by Ducas (2011). This shelf recognizes that for some trip purposes, travel up to a certain distance may not be undesirable.

2.5.4 Comparing metrics

These and other more novel impedance functions (including one inspired by seed dispersion models in botany) are summarized in Martínez and Viegas (2013). Others (e.g. Handy and Niemeier (1997), Kwan (1998)) have discussed the formulation and relative merits of such indicators and have implemented analytical software to calculate the indicators. The intended contribution of this dissertation is not to repeat such comparisons, but to consider accessibility measures as a general class from which specific formulations can be selected based on the needs of a specific analysis.

2.5.5 Regional indices

A general regional weighted average metric can be specified as

$$A(O, D, M, T, \tau) = \frac{\sum_{i=1}^{n}(p_i(O)a_i(D, M, T, \tau))}{\sum_{i=1}^{n} p_i(O)}$$

where

$a_i(D, M, T, \tau)$ is as defined above in Section 2.5.3

O is the selected origin class (e.g. residents, households, firms)

$p_i(O)$ is the population of the origin class O in zone i.

Finally, these measures can be normalized by the total number of opportunities in the region (yielding, for example, the percentage of a region's job accessible to the average household):

$$A'(O, D, M, T, \tau) = \frac{\sum\limits_{i=1}^{n}(p_i(O)a_i(D, M, T, \tau))}{\sum\limits_{i=1}^{n}p_i(O)\sum\limits_{j=1}^{m}q_j(D)}$$

2.5.6 Computation

The analyses in this dissertation rely primarily on two open-source software packages, Analyst Server [5] and OpenTripPlanner/R5 [6]. As shown in Figure 2.12, the administrative interface of Analyst Server allows for managing transit networks following the general transit feed specification (GTFS), road and pedestrian network data downloaded from OpenStreetMap (OSM), and georeferenced socioeconomic data representing opportunities to be accessed (e.g. in shapefile format).

With these inputs loaded, algorithms allow for rapid calculation (in about 6 seconds) of travel times (maximum, minimum, or average across a specified time window, assuming either a random departure or a departure timed to scheduled service) along the combined road/pedestrian and transit networks from a specified origin to all destination zones within a region[7]. The application programming interfaces (APIs) of these packages allow the parameters discussed above (O, D, M, T) to be modified easily. Service parameters of the underlying transport network can also be modified on-the-fly. A notable example is that route schedules can be converted between explicit timetable representations and headway-based representations, with the subsequent routing on a mixed frequency- and schedule-based network conducive to sketch planning.

These sketch planning analyses allow users to understand the first-order accessibility impacts of changes to the transit network. An important limitation is that they ignore interactions with other modes (e.g. cars) and land use. While such interactions are often central to project goals, the tools used here do not seek to predict or model them explicitly. Instead, users are encouraged to develop intuition about what such longer-term changes might be, based on interaction and iterative testing of multiple scenarios.

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[5] https://github.com/conveyal/analyst-server/

[6] https://github.com/conveyal/r5

[7] see Conway et al. (2017) for details of recent updates the R5 algorithm

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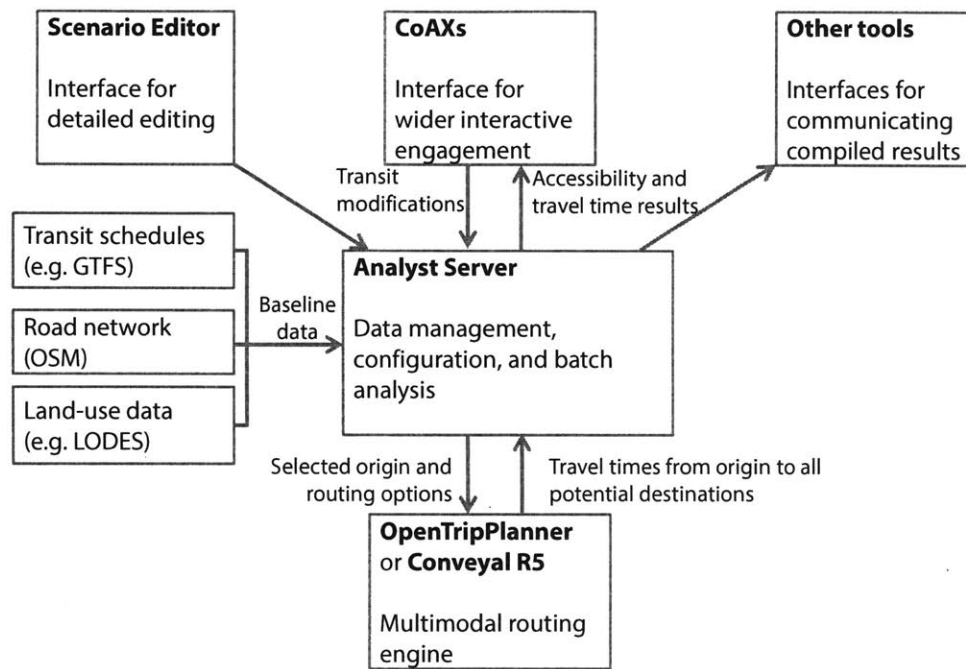
Figure 2.12: Computation modules

2.6   Conclusion

While accessibility can be formulated and calculated in many different ways, it fundamentally forces the recognition that space is not an empty or isotropic container. This recognition challenges the logics of abstract space, opening new avenues for representation in a broad sense. By enabling clearer understandings of complexities of urban places and flows, as well as the dynamics of functional centrality, accessibility may empower stakeholders to participate more meaningfully in spatial planning that shapes the city. Martens (2017) outlines three recommendations for accessibility metrics to further transport justice:

1. Use multiple accessibility measures in assessment

2. Account for differences between people

3. Keep measures simple and easy to communicate, to support democratic deliberation

These practical guidelines comport with the theory discussed in this chapter and guide the following chapters. Deliberation is the focus of Part II of the dissertation, and different ways to adjust accessibility metrics, in part to account for differences between people, is the focus of Part III.

Part II

Collaborative Accessibility-Driven Transit Planning

Chapter 3

Collaborative Planning and Accessibility

The demand [for opening the conversation about accessibility metrics] will come from outside the agencies. The demand will come from advocates for people to make sure that their needs are met.
— Stephanie Pollack, Massachusetts Secretary of Transportation
at a Brookings Institution discussion on accessibility metrics in January, 2017

Though the planning of urban transport projects is a spatial endeavor, transportation experts concerned with congestion delays have tended to overlook the spatial complexities of such projects (Handy and Niemeier (1997), Bailey and Grossardt (2010)). Hanson (2015) maintains that "from its inception, transport planning has focused on 'saving' time" (p. 3). This attention to predicting total trips, and the time saved for each of them, tends to neglect how "every transportation decision entails both connecting places together and excluding or bypassing other places" (Sheller, 2015, p. 13).

Measures of accessibility – the potential to reach destinations as determined by locations' relation to wider transport and land-use systems – explicitly integrate urban space and consider transport impacts more holistically. Despite the appeal of this holistic perspective and the availability of accessibility modeling tools, such tools "are not widely used to support urban planning practices" (te Brömmelstroet et al., 2014, p. vii). This "implementation gap" in transport planning persists despite concerted efforts to improve tools' functionality, interactivity, and user-friendliness (te Brömmelstroet, 2013).

The bureaucratic nature of transport agencies tends to reinforce this "implementation gap" and relates to another "gap," one between expectations of technical experts and the public regarding the role of public involvement (Bailey and Grossardt, 2010). In part because of the indirect incidence of many public transport impacts, "public participation for transit projects faces a number of unique challenges" (Casello et al., 2015, p. 88). These challenges can spur mistrust and conflict, which in turn inhibit transparency and receptiveness to new approaches.

Given that "black boxing and competing analyses (non-transparent, non-understandable, incomprehensible assumptions, etc.)" are a barrier to adopting accessibility tools (Papa et al., 2016, p. 16), it may be worthwhile to align accessibility tools with calls for broader participation. As Lucas (2012) argues, "accessibility analyses must reach beyond 'black box' technical assessments to include consideration of a much wider range of cultural, lifestyle, and experiential barriers... identified by the people who are affected" (p. 238). Put another way, for new planning tools to be adopted in practice (at least in the United States) they must be "coupled with credible participatory processes" (Ramasubramanian, 2011, p. 400). Some forms of participation rely on deliberation, which can be defined as decision-making "through dialogue, exchange and mutual learning, rather than through the mere aggregation of individual interests through voting" (Quick and Bryson, 2016, p. 160). If accessibility-based tools can help bridge the expectation gap about public involvement by enabling effective deliberation, they may be recognized as more valuable, thereby encouraging adoption and bridging the implementation gap.

Public involvement is used here to connote both targeted stakeholder engagement, in which implementing agencies curate support of advocates and elected representatives, and public participation, which includes more open forms of outreach, hearings, open houses, and consultations. In either case, attitudes toward a project are shaped along substantive and procedural dimensions. That is, participants' enthusiasm and advocacy for (or against) a project arise from their perceptions of both the project's merits and the implementing agency's credibility. Members of the public who do not trust an agency's intentions in participation (see Arnstein (1969)) or competence are unlikely to advocate for a project, even if they would support it on its merits alone. Conversely, effective public involvement can help implementing agencies, stakeholders, and members of general public achieve better outcomes through co-creation and consensus (Quick et al. (2015), Susskind and Cruikshank (2006)). For transportation projects in particular, dialog requires ways to access others' knowledge, which may be siloed by expertise (e.g. differing jargon of transportation engineers and land-use planners).

This part of the dissertation argues that the spatial nature of accessibility concepts, operationalized in a an interactive mapping interface to support collaboration, makes them a promising basis for deliberative public involvement in transit planning. More specifically, Chapter 4 presents exploratory work to identify interactions based on an an accessibility-based mapping tool (dubbed Collaborative ACCESSibility-based stakeholder engagement system, or CoAXs) that may foster social learning. CoAXs draws on accessibility concepts to support shared understanding among and between groups of planning officials, key stakeholders, and members of the general public in stakeholder engagement for transit projects. Chapter 5 builds on this work and presents the findings of a more experimental research design to test the value of CoAXs. First, this chapter reviews recent literature on spatial planning support systems and the common analysis features that underlie CoAXs.

3.1 Literature review: co-creation and spatial planning support systems for transit

Through their time and movement, users participate actively in transit's production, in contrast with other public utilities (Mohring, 1972). Rapidly proliferating information and communication technologies (ICTs) are further shifting consumers "from being passive, isolated, and unaware to being active, connected, and informed" (Gebauer et al., 2010, p. 514).

An orientation toward co-creation, "the active participation of customers in designing and implementing [public-transport operators' processes and systems," can help transit agencies navigate these new trends (Gebauer et al., 2010, p. 511). Gebauer et al.'s (2010) recommendations, drawing on experiences of the Swiss rail operator (SBB), are based on an assessment of five areas for personalizing the operator-customer relationship: customer engagement (e.g. promotions, communication channels), self-service (e.g. automated ticketing technology), customer experience (e.g. efforts to make service pleasant and instill loyalty), problem-solving (e.g. online trip planning and recovery of lost personal belongings), and co-design (e.g. coordinating service for special events). They judge that the last area, co-design, "has been rather under-utilized compared with the other four co-creation activities)" (p. 524). This underuse seems especially true for longer-term capital and corridor planning.

In the United States, though "conceptions of planning as collective design" are emerging (Klosterman, 1997, p. 53), longer-term transportation infrastructure planning has lacked true co-design. Even basic public involvement for transportation projects "has been, and in many cases continues to be, highly problematic" (Bailey and Grossardt, 2010, p. 60). Gaps between different types of stakeholder knowledge (e.g., "experts" and "non-experts" [Fischer (2000)]) are a major reason such engagement has been so problematic. Describing a participatory transport planning exercise in Ghana, Jones et al. (2015, p. 21) distinguish and seek to integrate, "tacit knowledge, which is personal and experiential," and "explicit knowledge...gained through data-driven experimentation, empirical analysis, development of theoretical understanding, etc." Te Brömmelstroet and Bertolini (2012) also use this distinction in differentiating between the expertise of different professional planners.

Ideally co-creative planning would extend beyond merely integrating different types of knowledge, to generate new knowledge through a process of social learning. (Innes and Booher, 2004, p. 428) describe such possibilities:

> "When an inclusive set of citizens can engage in authentic dialogue where all are equally empowered and informed...everyone is changed...They can work through issues and create shared meanings as well as the possibility of joint action. They can learn new heuristics."

Supporting true co-design, and generating new knowledge, requires bridging the "implementation gap" through spatial planning tools that support productively overlapping content

and relational spaces.

Research on the "implementation gap" considers why planning tools that provide novel representations of urban space are not adopted by practitioners. These tools can be defined in various ways (Klosterman (1997), Geertman (2006)) and classified according to intended audience (Balram and Dragicevic, 2006). Haklay (2010) uses "collaborative GIS" (CGIS) to denote a range of geospatial technologies used collaboratively by groups. CGIS includes planning support systems (PSS), which have components designed for relatively small groups of technically proficient users (te Brömmelstroet and Schrijnen, 2010), and public participation GIS (PGIS), which is designed for a wider range of participants. To reiterate, the premise of this research is that extending accessibility-based PSS to more comprehensible PGIS tools could encourage the adoption of accessibility measures. But supporting communication with and between diverse participants in open public processes implies additional design challenges (Haklay, 2010).

These challenges arise at the individual and group levels (see te Brömmelstroet (2013)), echoing social learning literature that recognizes "the content of the problem and the relational context are interdependent aspects of the collaborative situation" (Barron, 2003, p. 307). This interdependency makes the evaluation of CGIS tools a complex task. Jankowski and Nyerges (2003) propose a framework of convening, process, and outcomes constructs, and te Brömmelstroet et al. (2016) draw on design research to suggest the aligned context-intervention-mechanism-outcomes logic for evaluation . Goodspeed (2015) emphasizes the importance to CGIS evaluation of "dialog quality," an indicator of social learning, which positively correlates with "learning infrastructures" of engagement, alignment, and imagination. The framework proposed in Figure 3.1 draws on the above to consider how a tool like CoAXs could foster relational and content spaces that are conducive to social learning, basic learning *foundations* of engagement and attention (see Barron (2003)), and learning *structures* of alignment and imagination.
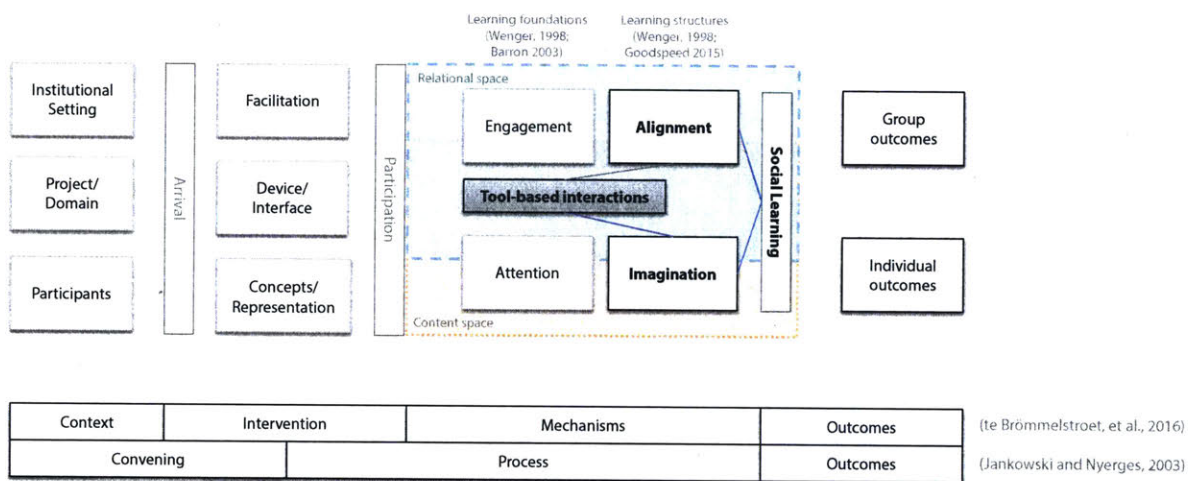
Figure 3.1: Theoretical framework, drawing on collaborative GIS and social learning literature

Context, intervention, and outcomes are discussed in the following chapters. Here, it is

important to stress that accessibility is central to the concepts represented in the CoAXs interface and emphasized by facilitation. Accessibility concepts may thus help shape content and relational spaces that spur certain interactions, leading to enhanced learning structures (alignment and imagination), which in turn foster social learning.

3.1.1 Individual-level interactions and content challenges

At the individual level, human-computer-interaction and user-centered design perspectives have structured extensive CGIS research (Haklay and Tobón (2003), MacEachren et al. (2005), Haklay and Skarlatidou (2010)). Effective tools must help users think through the varied "spatial reference frames" in play (Davies et al., 2010, p. 20). Experience-based mental maps of urban space may be highly distorted with respect to the cartographic content on a screen and the geographical space it represents. Lynch (1960) documents how residents familiar with a city rely less on link-based mental maps and "increasingly on systems of landmarks for their guides" (p. 78). This tendency to remember key experiential points, rather than the links of travel given prominence on transport maps, may create particular challenges for transportation models and applications of CGIS as compared to more general land-use planning applications (see Manley (2014)). Adequately representing dynamic and complex urban space through static maps, already a shortcoming of the "abstract" representations of technocratic planning, is complicated further for transportation planning because of how users perceive mobility (see Chapter 2). .

An access perspective can encourage localization and adjustment based on personal experience. Individual access emphasizes personalized abilities and identities, requiring interfaces that allow users to vary parameters like walking speed and to select specific origins (e.g. zooming into homes) and destination types (e.g. jobs in a certain sector requiring a certain level of qualification). Short of the detailed methods of Hägerstrand (1970) or the full "geo-narrative" approach of Kwan and Ding (2008), tools can help participants locate personally relevant points of interest on a map and use these locations to discuss experiences and adjust model parameters. Such localization and adjustment can ground deliberation in "local realities and citizen interpretations" (Fischer, 2000, p. 187), potentially increasing public acceptance.

3.1.2 Group-level interactions and relational challenges

Beyond these challenges of individual usability and spatial cognition are questions about how CGIS can foster "richer deliberation, expanded access, and effective communication" between diverse users (Elwood, 2011, p. 388). This PGIS research focuses on representation not in the sense of cartographic visualization, but of who is present, who interacts with the tools, and whose voice matters (Sieber (2006); Dunn (2007)).

Such questions of group dynamics and broader sociopolitical context have been underem-

phasized in CGIS research relative to analytical functionality and usability (Haklay (2010), te Brömmelstroet and Schrijnen (2010), Arciniegas et al. (2013)). Recent research has considered facilitators' roles (Pelzer et al., 2015) and intermediary constructs of relational quality such as satisfaction, consensus, and cohesion (te Brömmelstroet, 2013). Yet of the 30 communicative strategic PSS cataloged in te Brömmelstroet (2013), only five measure communication, one measures credibility, and none measures commitment or cohesion. te Brömmelstroet et al. (2014) and te Brömmelstroet et al. (2016) analyze European case studies of accessibility-based PSS, but in these cases users were predominantly technical experts, sidestepping questions central to wider participatory applications. They also dedicated up to 8 hours to meetings over the course of 6 weeks, which may be too demanding on participants time for public participation. Standalone web interfaces have been developed that are easily interpretable and communicable (e.g. Páez et al. (2013)), but these have not been widely tested for structured public involvement. Papa et al. (2016) survey developers of 21 European accessibility instruments, of which only 5 were designed to be usable by ordinary citizens.

Sheller (2015) calls for more mobility studies research into "how different social actors use narratives to frame transportation issues and shape decision-making contexts" (p. 14), issues particularly relevant for implementing CGIS. Bailey and Grossardt (2010) offer strong arguments for technologies designed to facilitate in-person mutual learning and foster "dialogue that otherwise is hard to encourage," and help " 'make sense together' (Forester 1989, 17), even if this dialogue does not take the form of a classic consensus" (p. 70). Their case studies present relatively straightforward measures of individual user-reported satisfaction, but tend toward aesthetic and localized impacts of projects, rather than the wider network effects of transport. Such network effects, and how they map onto geographical space, are a crucial and under-researched aspect of transportation CGIS. These often non-intuitive effects create challenges of representation, in the conceptual sense of representing space cartographically and in the relational sense of broader representation, unique to transportation projects.

Specific features of rapid accessibility analysis could be exploited to facilitate social learning about complex impacts, in which participants who are not technical experts learn about the possibilities of proposed projects and at the same time technical experts learn local knowledge from the participants. Such mutual learning should be based on deliberative dialog about problems and ranges of potential solutions (Fischer, 2000). If dialog is to support mutual learning effectively, the tools prompting it must be sufficiently responsive. Accessibility analyses that forgo computation-intensive agent-based or iterative assignment models, and provide nearly instantaneous results, can align well with this priority. Accessibility maps can also support dialog and deliberation because they map abstract network effects onto a shared map-based representation, enabling intuitive comparisons between different locations, and supporting discussions of equity across different areas (Manaugh and El-Geneidy (2012), Lucas (2012), Lucas et al. (2015)).

3.2 Tool features

The custom CoAXs interface consists of a single-page web application with two zoomable and pannable maps; the accessibility map displays isochrones and travel time savings, and the corridor editor map highlights transit corridors for which service can be modified.

The core accessibility concepts represented in CoAXs are isochrones, comparative travel time maps, and catchment statistics for selected opportunities (as depicted in Figure 3.2). These representations are created on demand using OpenTripPlanner/R5 and Analyst Server and its API, as described in subsection 2.5.6. Modifications to transit service, including (de-)activating routes, changing route frequencies and speeds, and specifying different departure time windows and assumptions about waiting time, can also be specified via the open API. By allowing modification of selected service parameters and scenarios, and returning results in about six seconds, CoAXs seeks a middle ground for deliberative public involvement, between unconstrained generation of alternatives and the presentation of a small number of pre-analyzed ones.

The focus on rapid computation precludes incorporating feedback loops (e.g. with traffic congestion using microsimulation or land use with an integrated regional model), which often require timely computation and data for calibration. Even if rapid iterative computation allowed these feedback loops to be incorporated, they might need significant assumptions to be made; if these assumptions had to be pre-programmed, as they probably would be to avoid information overload for participants, the tools would be subject to the typical critiques of technical-rational planning (see Chapter 2).

CoAXs is designed for collaborative sessions led by trained facilitators. Facilitators are provided templates but respond flexibly to different audiences as they see fit. The general stages of the template are summarized below and in Figure 3.2.

1. Participants introduce themselves, agree on group communication, and frame the session by discussing the general purpose of public transport.

2. Facilitators ask participants to locate specific landmarks in order to introduce map features.

3. Participants are prompted to move an origin marker to personally relevant locations (by tapping on their username to activate pre-loaded points of interest, or by manually dragging a "pin"), sharing personal experiences of trip patterns and comparing them with how CoAXs represents those patterns through the resulting isochrones for the baseline scenario.

4. Facilitators introduce the concept of accessibility by highlighting catchment statistics related to the isochrones (e.g. the number of jobs in different industries accessible within one hour from selected origins) and asking participants to compare catchment statistics from different locations. These catchment statistics are represented on a plot
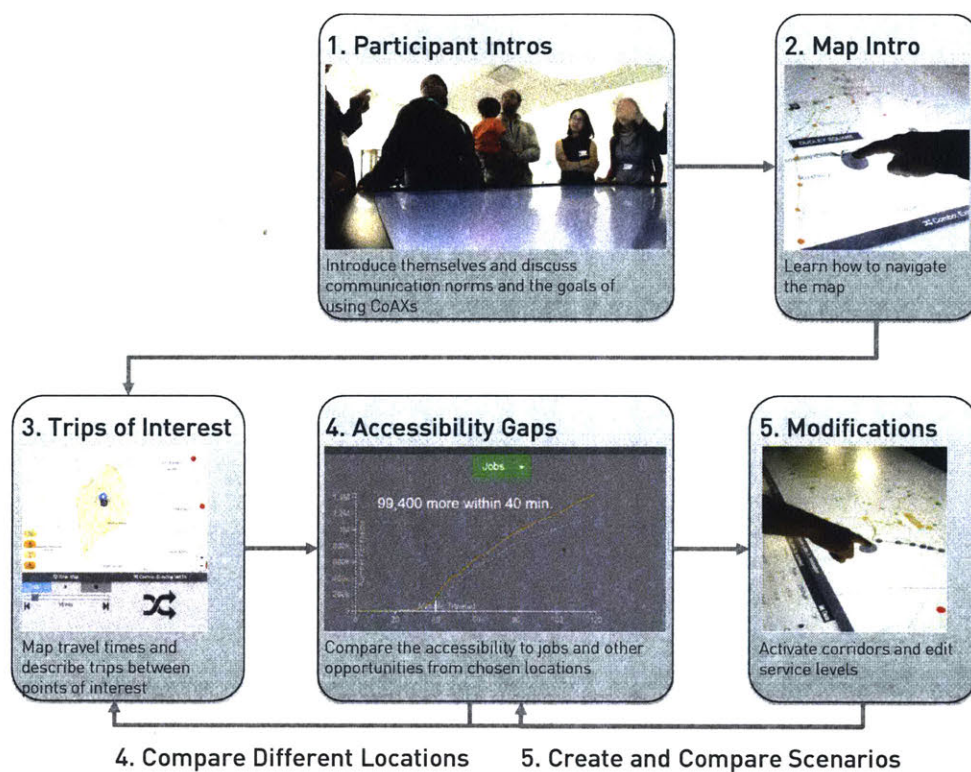
Figure 3.2: Participant activities during facilitated testing of CoAXs

of cumulative opportunities – the same type of representation described and shown in Sections 2.5.3, 7.4, and 8.3).

5. An example alternative scenario (e.g. with an improved bus route) is introduced. Participants compare the travel time and accessibility impacts of this scenario relative to the baseline of current transit service, then create their own scenarios by modifying assumed frequency, activating different corridors, etc.

3.3   Tool evaluation

Iterative rounds of focus groups and user testing have guided the development of CoAXs. Much has been written about technology-enabled group interactions through the lens of human-computer interaction. The hypotheses in the following two chapters seek to elucidate slightly different findings. A round of public workshops in 2015 explored mutual learning between participants, as well as correlations between use of the map-based features of CoAXs and imagination, group alignment, and dialog quality. The results of this exploratory analysis are the focus of Chapter 4. Chapter 5 discusses a subsequent round of stakeholder engagement workshops in 2016, focused on how different framings of transit benefits affect

the scope of impacts considered and enthusiasm among groups of transportation advocates. This analysis seeks to isolate the role of an accessibility framing in helping participants understand and deliberate about the spatial impacts of transit projects. While the contexts and audiences differ slightly between the two sets of workshops, they are both meant to test the value of CoAXs, its interactive interface, and its accessibility framing, in supporting collective thinking and dialog.

Chapter 4

Exploratory Workshops

Transportation's remote impacts create unique challenges of representation. The preceding chapter contends that interactive accessibility-based maps can improve representations of transport in urban space, thereby supporting dialog and social learning in intertwined relational and content spaces. The research presented in this chapter seeks to determine what mechanisms can foster social learning in public engagement workshops using interactive accessibility mapping. Potential mechanisms include individual interactions (related to localization and adjustment based on personal experience) and tool-supported group interactions (related to deliberation enabled by rapid computation and easily comparable maps), as well as the reinforcement of learning structures such as imagination and alignment.

4.1 Hypotheses

Public workshops in October, 2015, at a municipal building in Boston's Roxbury neighborhood were designed to test four hypotheses using a pre-test/post-test design and mixed methods:

In the overall workshop:

1. Mutual learning occurs, as indicated by high degrees of reported social learning, and parity in reported dialog quality and overall learning between different classes of participants

2. Imagination and alignment correlate positively with overall learning and dialog quality

Regarding the use of CoAXs specifically:

3. Individual-level measures of interaction correlate positively with individual scores for

imagination

4. Group-level measures of interaction correlate positively with groups' average scores of imagination and alignment

The multi-level structure of the hypotheses is meant to avoid attributing to CoAXs learning that may instead result from other influences, such as facilitation.

4.2 Design and methodology

The overall approach taken to developing and evaluating CoAXs is an "iterative process of testing and refining, with focus on the 'underlying mechanisms' at play" (following Straatemeier et al. (2010, p. 582)). Both design-research and quasi-experimental methods are used, described below following the context-intervention-outcome logic (see Figure 3.1).

4.2.1 Context: social and institutional setting

Two bus rapid transit (BRT) corridors in Boston, opened in the early 2000s, have faced local criticism for circuitous routing and the lack of dedicated lanes in congested areas (see Zegras et al. (2016) for a discussion of BRT in Boston). Criticism is especially strong among some local activists and community-based organizations who view BRT as inferior transport reflecting bias against the predominantly minority residents of Roxbury, Dorchester, and Mattapan who live in a gap between the Red and Orange Lines of the MBTA (Mas, 2012). These racial issues, related partly to residential segregation in the region (see Figures 2.7-2.8 and 4.1), along with other issues including negative perceptions of bus service, create public involvement challenges for a local civic philanthropy's campaign promoting new BRT corridors. This philanthropy sponsored the development of CoAXs and its deployment in workshops to test the potential for encouraging mutual learning about BRT impacts.

4.2.2 Intervention: underlying concepts, interface, and facilitation

A version of the CoAXs interface was developed for the activation and modification of four BRT and one heavy rail corridor in Boston, and it was tested on large touchscreen (see Figure 4.2). Using the notation introduced in Chapter 2, participants moved a map pin to test multiple origins i, a slider to adjust τ, and a drop-down menu to change D between jobs in different industries. Mode M was fixed to walking and public transit, and T was fixed to 7-9 AM.

Figure 4.3 shows the overall participant flow in the exploratory public workshops. Upon arrival, participants completed paper entry surveys about demographics and prior involve-
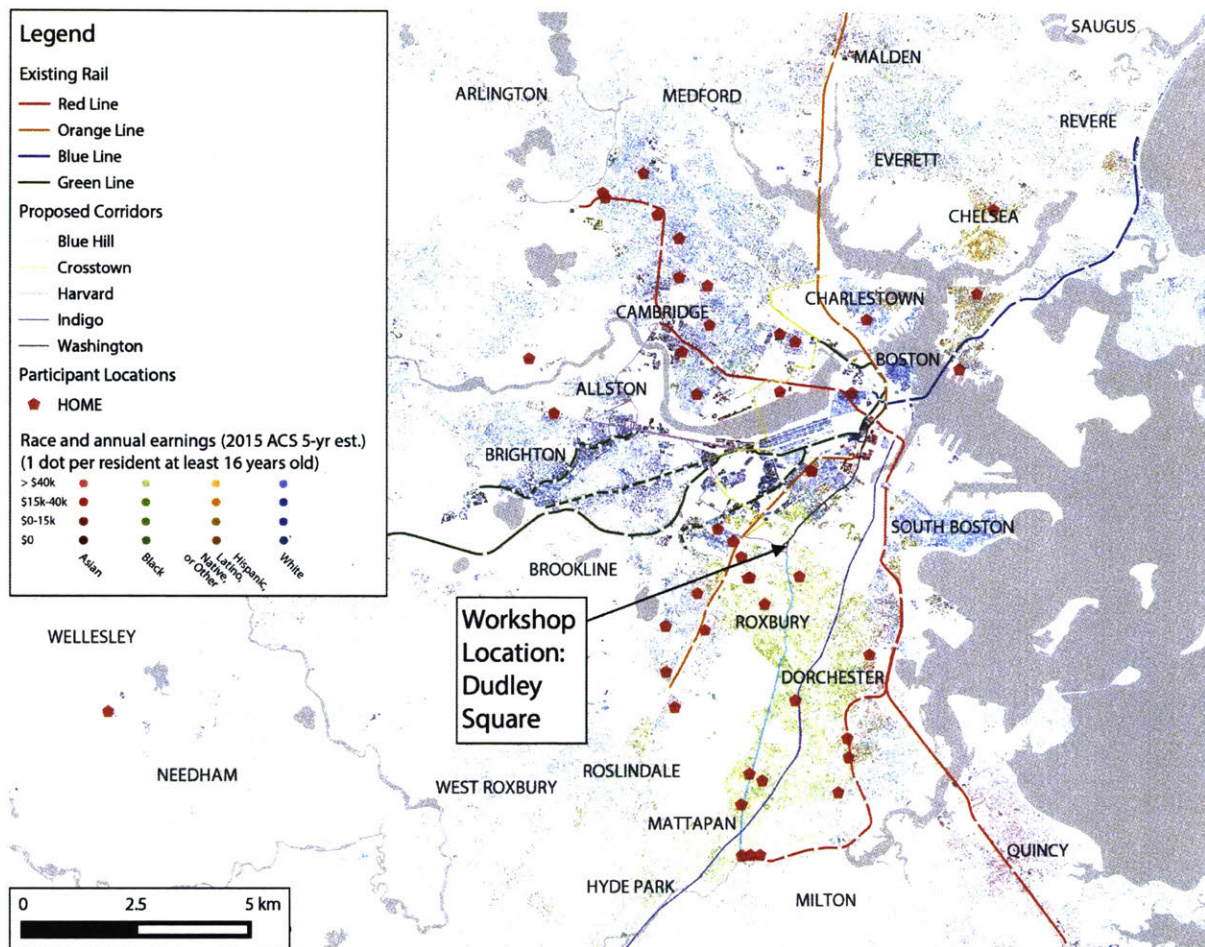
Figure 4.1: Participant home locations

ment in planning. They then input points of interest (e.g. home, work, school, recreation, and healthcare locations) to a simple digital map-based survey for later use. After a short introduction and dividing into randomly assigned groups[1], participants tested CoAXs and a separate visualization tool called CityScope in parallel (see Alrashed et al. (2015)). CityScope displayed localized impacts of BRT corridors using 3-D models, but only for a small number of pre-analyzed scenarios, whereas the live analysis capabilities of CoAXs enabled an expansive solution space (on the order of 10^{20} distinct scenarios). The different focus and functions of CityScope deter direct comparisons with CoAXs, but it does offer a quasi-control to gauge participant responses to tangible tools generally. After testing both tools, users completed an exit survey and participated in a debrief discussion.

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[1]The number of groups was adjusted based on workshop attendance, so that each group (up to 3 groups per workshop) would have between 3 and 5 participants. A group is uniquely identified by workshop letter and group number (e.g. workshop A's first group is group A1).

Figure 4.2: Testing CoAXs on a large touchscreen (Photo: Ryan Chin)

4.2.3   Outcomes: mixed methods evaluation

Participants were categorized by technical expertise and predisposition to skepticism, based on responses to the entry survey. Transportation/policy/planning experts were identified based on open-ended descriptions of professions. Participants reported the number of planning meetings they had attended in the preceding year, and the number of these meetings at which they learned something about the proposed project; the difference between the former and the latter was deemed an imputed score of skepticism (about learning in planning meetings), and participants with a non-zero score were classified as skeptics.

Video recorded during the workshops permitted subsequent coding of interactions and transcription of group conversation through computer-assisted qualitative data analysis software. Given the exploratory nature of this research, detailed interactions to code were not specified a priori; they were identified through iterative viewing of the recorded videos.

Scores for individual learning (an outcome of social learning) and dialog quality (an enabler of social learning) are derived from the exit survey. The exit survey included five-point Likert-type scales to indicate (dis-)agreement about overall learning, social learning, and functionality of each of the tools, as well as open feedback. Drawing on Goodspeed (2015), *dialog quality* was defined as the sum of the responses to four survey questions:
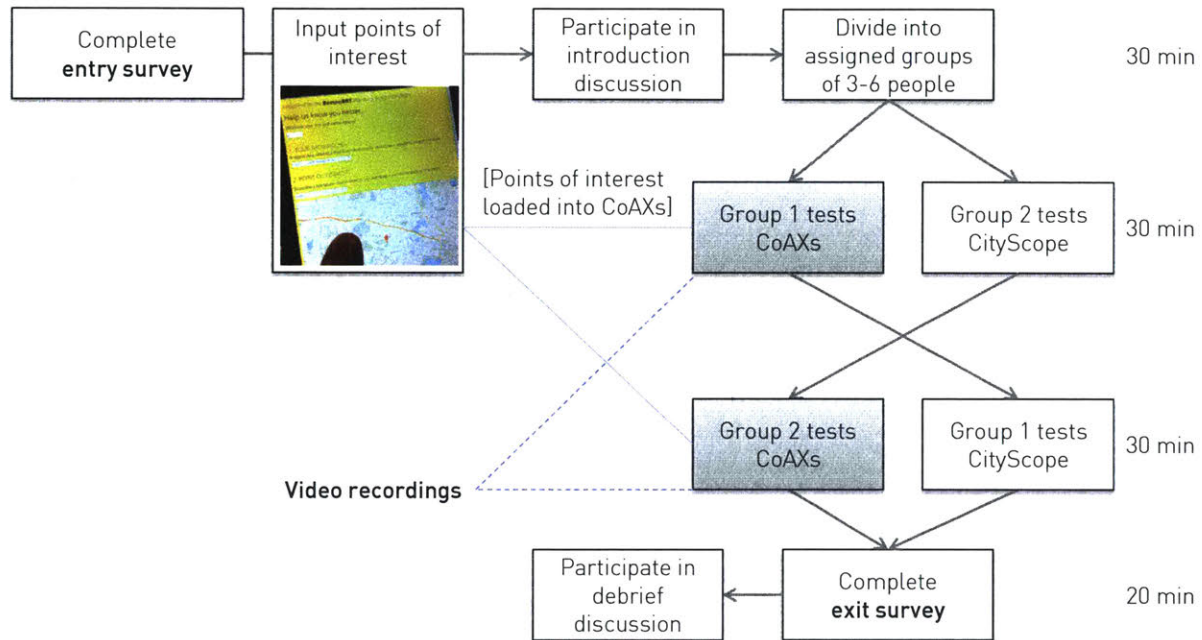
Figure 4.3: Flow of participants and information in exploratory workshops

1. I was able to get answers to the questions I asked

2. Workshop participants discussed issues in an open way

3. Participants were open to differences in opinion

4. I would support recommendations created by the participants of the workshop

As they do not control well for context, these dialog quality scores are not meant for direct comparison with other participation processes. The intended contribution is rather to identify individual and group interactions that might be correlated with structures that support social learning.

4.3 Results

Over the course of one week, six workshops were conducted. These workshops were open to the public and involved 53 total participants from a range of advocacy, policy, neighborhood, and professional organizations. Of these participants, 13 were classified as technical experts in transportation, policy, or planning, and 15 reported attending no public planning meetings within the preceding year. While this may be a more technically skewed audience than typical public planning meetings, it still represents a departure from much previous testing of accessibility instruments with expert planners.

4.3.1 Overall workshop results

Of the 53 participants, 43 completed at least part of the exit survey, as summarized in Table 4.1

Table 4.1: Overall Workshop Results, Individual-Level Descriptive Statistics (n = 43)

Measure	Range/Unit	Mean	Std. Dev
Reported Learning			
Open Dialog Index (*dialog quality*)	4-20 Likert scale	17.09	2.57
"Learned a great deal" (*overall learning*)	1-5 Likert item	3.98	0.89
"Learned through others' use of tools"	1-5 Likert item	4.25	0.91
"Learned through listening and conversing"	1-5 Likert item	4.30	0.81
"Helped others learn"	1-5 Likert item	3.45	0.99
Planning Background			
Meetings attended in past year (*PastMeetings*)	Count	2.85	2.94
Meetings with no learning in past year (*ImputedSkepticism*)	Count	0.59	1.29

The highest *skepticism* score was for a consultant who reported that she attended six meetings in the preceding year, but only learned at one of them (yielding a score of 5). The second-highest skepticism score (4) was assigned to two residents of Dorchester and Mattapan, one of whom had emailed organizers criticizing the workshops before attending. Figure 4.4 shows reported overall learning, segmented according to the planning expertise and skepticism classifications.

4.3.2 CoAXs-specific results

For the CoAXs-specific analysis, 36 respondents completed the tool evaluation portion of the exit survey. The resulting tool ratings are broken down in Figure 4.5. Due to gaps in the video recordings and other inconsistencies (e.g. groups where participants departed early), results for tool-specific interactions were valid for only 6 of the 11 groups, comprising 21
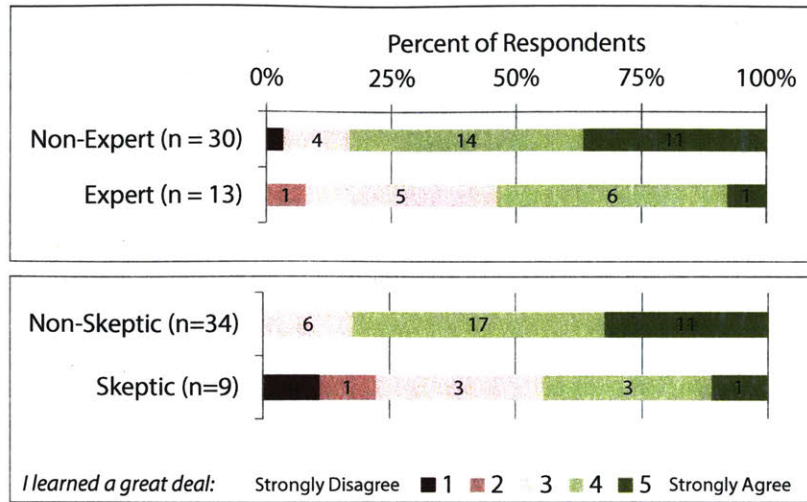
Figure 4.4: Reported Overall Learning

individuals. Table 4.2 summarizes tool ratings and coded interactions for these participants. In Table 4.2, actions by a given participant are tabulated (e.g. on average, each participant touched the screen [*Touch*] 10.2 times). Also tabulated are the total interactions by all users (i.e. by participants and facilitators) when the trip origin marker was located at a given participant's chosen location. For example, on average, the screen was touched 9.1 times while displaying isochrones from a location chosen by each participant, but the high standard deviation (8.3) suggests that such interaction varied widely by participant.
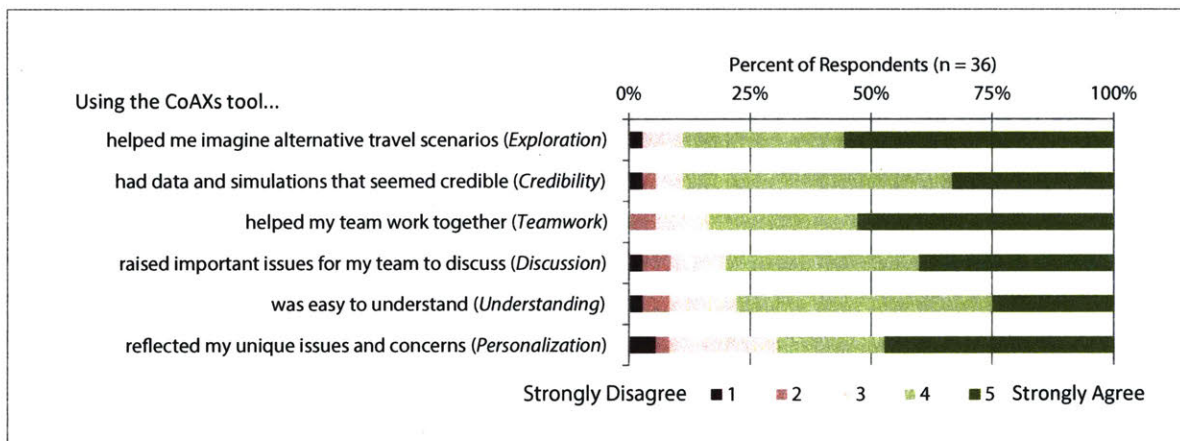
Figure 4.5: CoAXs Evaluation

Table 4.3 [2] aggregates some of the measures in Table 4.2 as well as other descriptions of group composition and interactions, such as the average number of trip origins tested per

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[2]Note that the total number of participants (sum of *Size*) in Table 4.3 is 23. Two of these participants did not complete the exit survey, which is why n=21 in Table 4.2.

Table 4.2: CoAXs-Specific Results, Individual-Level Descriptive Statistics (n = 21)

Measure	Range/Unit	Mean	Std. Dev
CoAXs Evaluation (wording based partly on Goodspeed, 2015)			
Raised important issues for my team to discuss (*Discussion*)	1-5 Likert item	4.14	0.99
Helped my team work together (*Teamwork*)	1-5 Likert item	4.10	1.06
Had data and simulations that seemed credible (*Credibility*)	1-5 Likert item	4.24	0.92
Helped me imagine alternative travel scenarios (*Exploration*)	1-5 Likert item	4.38	1.00
Discussion + Teamwork (Alignment)	2-10 Likert scale	8.24	1.92
Credibility + Exploration (Imagination)	2-10 Likert scale	8.62	1.79
Actions taken by participant			
Instance of speaking (*Speak*)	Count	18.0	12.8
Words spoken, as proportion of group total (*PctWords*)	Proportion	0.05	0.05
Gestures at connectivity map or control panel while speaking (*RefTool*)	Count	3.4	3.5
Refers to personal experience and access (*RefExp*)	Count	2.1	2.1
Refers to accessibility to jobs, etc. (*RefAcc*)	Count	0.8	1.1
Questions data, assumptions, or visualization (*QTool*)	Count	2.0	2.1
Touches or taps screen (*Touch*)	Count	10.2	6.6
Total user interactions while trip origin marker at participant's chosen location			
Number of times origin marker moved to location (*LFocus*)	Count	1.8	0.9
Gestures made at connectivity map (*LRefTool*)	Count	7.5	6.7
Personal experience and access referenced (*LRefExp*)	Count	1.8	1.6
Accessibility to jobs, etc., referenced (*LRefAcc*)	Count	1.5	1.6
Data, assumptions, or visualization questioned (*LQTool*)	Count	1.2	1.4
Touchscreen tapped (*LTouch*)	Count	9.1	8.3

participant (*LFocusAvg*) and instances of accessibility being discussed while the trip origin marker was placed at a specific location (*LAcc*).

Table 4.3: CoAXs-Specific Results, Group-Level

Measure	Range/Unit	Group A1	A2	B1	C1	D1	E1
Average of members' alignment ratings (*Group alignment*)	2-10 Likert scale	8.3	7.5	6.0	9.7	8.0	9.7
Average of members' imagination ratings (*Group imagination*)	2-10 Likert scale	9.0	7.3	8.5	8.7	8.8	9.7
Session duration (*Duration*)	Minutes	26.6	33.7	30.0	23.0	34.2	28.6
Number of participants (*Size*)	Count	4	4	4	3	5	3
Facilitator words spoken (*FacTalk*)	% of words	82	75	65	77	88	67
Facilitator taps on screen (*FacTouch*)	% of touches	57	45	31	31	42	18
Percent of participants who were black (*BlackPct*)	% of particip.	0	25	60	0	20	0
Time discussing personal experience (*ExpTime*)	% of time	3.7	8.9	6.5	5.4	4.1	5.5
Time discussing accessibility (*AccTime*)	% of time	28.4	6.2	2.9	26.0	21.2	18.4
Time questioning tool (*QuestTime*)	% of time	3.6	0.8	2.9	3.8	4.1	4.4
Words referencing map (*RefMap*)	% of words	28.0	19.6	13.4	21.8	21.1	18.2
Participant touch rate (*TouchRate*)	Touches per min.	1.0	0.9	1.5	1.7	1.5	2.3
Participant points tested (*LFocusAvg*)	Points per particip.	0.8	1.3	1.6	2.3	2.0	3.3
Accessibility mentioned with marker placed (*LAcc*)	Count	1	3	5	9	9	6

4.4 Analysis and discussion

As shown in Table 4.3, flow and duration varied considerably between the groups. The author helped facilitate each group's use of the tool, with support from an additional facilitator in workshops A and B, and a larger team of facilitators running the overall workshop. Using the CoAXs tool, facilitators played a dominant conversational role (speaking between 65% and 88% of words [*FacTalk*]) but were less dominant in terms of touchscreen interactions (between 18% and 57% of the screen touches [*FacTouch*]). Further analysis at the group level is included in subsection 4.4.4; overall workshop and individual-level results are discussed first.

4.4.1 Mutual learning in the overall workshop

Mutual learning can be gauged by how much the participants learned from each other, and whether there were gaps in reported learning along lines of expertise and skepticism. Table 4.1 shows strong agreement about learning through others' use of CoAXs and Cityscope (4.25/5) and through listening and conversing (4.30/5), but weaker agreement that participants themselves helped others learn (3.45/5). This result suggests limited mutual learning occurred between participants, and that facilitators drove social learning in the overall workshop.

In terms of gaps, non-experts reported higher overall learning than experts (see Figure 4.4), which may suggest that CoAXs and CityScope were simple enough for lay people to

Table 4.4: Correlation matrix, Overall Workshop (n = 38)

		Overall learning	Dialog quality	Skepticism	Discussion	Credibility
Outcome variables	Overall Learning	--				
	Dialog Quality	0.71	--			
Control	*Skepticism*	−0.51	−0.43	--		
Alignment	*Discussion*	0.45	0.60	−0.49	--	
	Teamwork	0.50	0.54	−0.60	0.73	
Imagination	*Credibility*	0.48	0.64	−0.59	0.51	--
	Exploration	0.62	0.66	−0.59	0.52	0.65

understand, but simplistic for experts. Gaps in dialog quality were mixed. The scale, with a range of possible values from 4 to 20 and a mean of 17.09, was found to have acceptable internal consistency (Cronbach's $\alpha = 0.78$)[3] , supporting its use as a measure of social learning. Dialog quality was not rated differently by experts versus non-experts (17.42 vs. 16.31, $p = .21$ in a two-sided Student's t-test), supporting the case for these tools to address the "expectation gap" about public involvement. Skeptics, as compared to non-skeptics, reported lower overall learning (see Figure 8) and significantly lower dialog quality (14.67 vs. 17.68, with $p = .03$ in a one-sided Student's t-test). While these results are not surprising, an ideal process would arguably have dialog quality rated equally highly by skeptics.

These responses about the overall workshop are not necessarily valid for assessing CoAXs alone, because they do not control for factors such as overall facilitation and context.

4.4.2 Positive correlations between learning structures, reported overall learning, and dialog quality

Table 4.4[4] shows reported *overall learning* and *dialog quality* correlate strongly and positively with the average rating of the CoAXs and CityScope tools' ability to support *discussion*, *teamwork*, *credibility*, and *exploration* (see Table 4.2 for the specific phrasing of the related questions). All of these measures correlate strongly and negatively with *skepticism*. *Discussion* and *teamwork* are strongly correlated ($\rho = 0.73$) , as are *credibility* and *exploration* ($\rho = 0.65$). These pairs were summed to create the indices *alignment* and *imagination*, which have good internal consistency (Cronbach's $\alpha = 0.82$ and 0.79, respectively).

The indices representing *imagination* and *alignment* are included as independent variables

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[3]see Cronbach (1951)

[4]While 43 participants responded to at least part of the exit survey, only 38 completed the survey in its entirety.

Table 4.5: Regression Results for Dialog Quality, Overall Workshop (n = 38)

	Model 1			Model 2			Model 3		
	Coeff.	SE	p-val	Coeff.	SE	p-val	Coeff.	SE	p-val
Const.	3.57	2.01	0.084 .	3.52	2.08	0.099 .	3.82	2.97	0.207
Alignment	0.59	0.28	0.041 *	0.58	0.29	0.051 .	0.57	0.3	0.065 .
Imagination	1.07	0.27	0.000 **	1.08	0.28	0.000 *	1.06	0.3	0.001 **
PastMeetings				0.01	0.1	0.896			
Skepticism							-0.04	0.35	0.908
Adj. R^2	0.54			0.53			0.53		

$** \ p < .01, \ * \ p < .05, \ . \ p < .10$

in ordinary least-squares regression models explaining *dialog quality* (see Table 4.5). *Imagination* correlates positively and significantly ($p < .01$) with *dialog quality*. The relatively strong explanatory power (adjusted $R^2 = 0.54$ for Model 1) supports these learning structures as valid intermediate indicators of the tools' effectiveness in fostering social learning. They also seem to capture the effect of past meeting attendance (*PastMeetings*) and skepticism toward learning in planning meetings, as neither of these variables is significant at reasonable confidence levels (see Model 2 and 3 results in Table 4.5).

4.4.3 CoAXs interactions promoting imagination at the individual level

Quantitatively, *imagination* scores for CoAXs alone were tested as the dependent variable in ordinary least-squares regression models of individual interactions (see Table 4.6). Even controlling for predisposition toward skepticism, the number of references a participant made to personal experience (*RefExp*) correlates negatively with imagination. This surprising result – the more a participant referred to personal experience using the tool, the lower they rated it for supporting credibility and exploration of alternatives – may demonstrate the need for more realistic representations of actual transit service, rather than just service as scheduled. Questioning the tool's features, underlying data, and modeling assumptions (*QuestTool*) is positively correlated with imagination, while the total number of times the origin marker was moved to a participant's location (*LFocus*) is negatively correlated.

As discussed above, in the overall workshops, fostering credibility and exploration was an important factor in the measure *imagination*. Discussion of personal experience tended to stress unreliability (how operated service deviates from the scheduled service represented in CoAXs), especially for buses, which might have undermined the credibility of CoAXs. An illustrative example is a participant who tested a bus journey, said the tool did not reflect her experience, then tested a journey made by rail and judged, "That's about right... because it's all trains; the rapid transit is much more reliable than the bus." Participants also raised localized operational concerns such as non-enforcement of bus-only lanes, local knowledge

saliently linked to specific places (Lynch (1960), Fischer (2000)). These examples highlight potential interdependence between the individual and group, or concept and relational spaces of the workshop; participants who felt that the tool's conceptual representation of their travel experience was not credible might be less inclined to trust or explore representations of other participants' travel. Better incorporating operational and reliability factors could improve the ability of CoAXs to support credibility and openness to exploration, the factors underlying *imagination*.

Other qualitative data suggest that accessibility concepts supported individual learning and empathy about wider impacts. Of the 43 responses to the open question "how might corridors like those we discussed today impact others' travel in the region?", 12 referenced accessibility, with comments such as "possible to reach more jobs and attract jobs to new areas." These 12 respondents skewed toward technical experts, who also tended to overlook more concrete impacts such as rider comfort. Responses to other open questions, in the survey and debrief discussion, noted it was powerful to see the "impact of new corridors in terms of economic development" and to "find ourselves, and others, in the data."

Table 4.6: Regression Results for *Imagination*, CoAXs Tool (n = 21), using codes from Table 4.2

	Model 1			Model 2			Model 3			Model 4			Model 5		
	Coeff.	SE	p-val	Coeff.	SE	p-val	Coeff.	SE	p-val	Coeff.	SE	p-val	Coeff.	SE	p-val
Const.	9.85	0.39	.000**	9.44	0.41	.000**	10.92	0.63	.000**	10.76	0.84	.000**	9.06	0.52	.000**
Skept.	-0.52	0.21	.026*	-0.5	0.2	.021*	-0.68	0.18	.001**	-0.65	0.22	.009**	-0.39	0.21	.084.
RefExp	-0.42	0.14	.007**	-0.49	0.13	.002**	-0.45	0.11	.001**	-0.46	0.12	.001**	-0.5	0.13	.001**
QTool				0.25	0.12	.056.	0.22	0.1	.050.	0.23	0.11	.056.	0.27	0.12	.043*
LFocus							-0.74	0.26	.012*	-0.7	0.29	.030*			
LRefAcc										0.05	0.84	.771	0.21	0.17	.244
Adj. R^2	0.52			0.59			0.71			0.69			0.60		

$** \ p < .01, \ * \ p < .05, \ . \ p < .10$

4.4.4 CoAXs interactions correlated with group-averaged alignment and imagination

Groups A2 and B1 had the lowest average levels of *imagination* and *alignment*, and discussed personal experience at length throughout the sessions (see Table 4.3), often using it to critique results shown. Conversely, groups A1, C1, and D1 spent the highest percent of time discussing accessibility, with limited time spent on personal experience, and had relatively high average ratings for how well CoAXs supported imagination and alignment. Causality in these relations is unclear, though it seems likely that groups predisposed toward trust and teamwork would be more likely to follow the planned facilitation stressing accessibility and less likely to dwell on personal experience. A technical failure for group A2 disrupted the planned script and led the facilitator to control most of the map manipulation. This failure, compounded by the coincidental membership in this group of a participant with one of the highest imputed skepticism scores, likely explains the low average alignment score (second lowest of all groups, as shown in Table 4.3).

The groups with the highest levels of *group alignment* and *group imagination* (C1 and E1) were the smallest, were relatively homogenous in terms of race and age, and had the highest rate of participant touches, as well as relatively high amounts of time spent questioning the tool. The negative correlation between the percent of black participants and group alignment ($\rho = -0.92$, for the six groups shown in Table 4.3) has a number of potential explanations. The groups with the highest proportion of black participants (groups A2 and C1) coincidentally diverged most from the facilitation script, due partly to the technical failure described above. Another potential explanation is that, with a larger context of racial segregation in Boston residential locations, experiences of public transit in the predominantly black neighborhoods of Roxbury, Dorchester, and Mattapan differ substantially from experiences in other parts of the city with more reliable transit (e.g. rail-based), and that the resulting differences in perceptions of transit impede group alignment. The identities and cultural competence of the facilitators also likely played a role; the lead CoAXs facilitator in all of the workshops was multi-racial (white/Asian).

The strong positive correlation between *group imagination* and the percent of time spent questioning the tool (*QuestTime*) at the group level ($\rho = 0.93$) agrees with the analogous finding at the individual level, strongly suggesting that questions about tool assumptions should be actively encouraged. *TouchRate* is also positively correlated with *group imagination* ($\rho = 0.74$), though there may be a confounding effect of participants with a predisposition toward both interacting with and trusting the tools.

The average number of times accessibility was tested from points of interest per participant (*LFocusAvg*) correlates positively with both group alignment ($\rho = 0.61$) and group imagination ($\rho = 0.58$). This result contrasts with the significant negative correlation between number of times a point of interest was tested (*LFocus*) and imagination at the individual level (see Table 4.6), suggesting that while localization may not foster exploration and credibility at the individual level, seeing impacts compared from locations relevant to other

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participants may support these learning structures at the group level.

More intricate social mechanisms were difficult to quantify. Specific sequences seemed to prompt periods of heightened engagement among all participants in a group. The following transcript excerpts (in which **F** is the lead facilitator) are examples from the two groups with the highest *group imagination* scores, and some of the highest *group alignment* scores:

Dialog from Group A1 (4 participants)

AQ: Let me look where I'm moving, which is... [AQ drags pin to indicate his new home]

F: ...What we can see here in this blue line is the base case. And there's a yellow boundary that represents your travel time boundaries in the new scenario.

[AQ moves slider without explicit instruction]

CD: Not that different.

WU: Not that different.

F: ... Let's try another spot.

JE: I'm curious about moving it to Allston. [JE drags pin]

F: To Allston.

JE: So if you live in like, now, Lower...

F: So right now you have to rely on the 66 bus [Participants groan]...

AQ: You're really getting accessibility, but it's not evenly distributed along the corridor... Some people are going to do better than others.

Dialog from Group E1 (3 participants)

F: YK, that Pink Line might help for you, right?

[YK taps username without explicit instruction]... Not bad.

AG: Oh, because you can make that connection to the Green Line.

YK: Yes.

...

F: So how many more jobs within an hour?

[YJ taps data for scenario scorecard] 1300, not bad.

F: GP, what about for you?

[GP taps username] So about the same.

GP: Oh yeah, the same...

YK: So basically this part [YK gestures at map showing where there would be a significant change in travel time] is just quite poorly served right now.

AG: It's that cross... [AG gestures at map to indicate crosstown travel]

These two deliberative episodes share a number of common features. A participant, tapping or gesturing without explicit instruction from the facilitator, focuses the attention of all participants on the screen. The conversational opening created by a short calculation, or by the participant curtailing their speech to point at a transit corridor or location on the map, is then filled by other participants, sometimes mimicking each other verbatim. Such episodes of verbal "convergence" (see Quick et al. (2015)) seem to be associated with empathy (e.g. **AG** realizing **YK** would make a connection with the Green Line, or participants in group A1 groaning about the notoriously unreliable Route 66 bus), supported by clear visual representations of accessibility impacts for specific locations.

These episodes suggest that specific features of CoAXs and its accessibility framing of the network impacts of transport may prompt social learning through deliberation, convergence, alignment, and empathetic imagination of others' travel.

4.5 Lessons from exploratory workshops

This research tested to what extent interactive spatial tools, and in particular accessibility maps, might support social learning in participatory public transport planning. Interactions related to accessibility concepts were quantified at the individual level and group level, as were the learning structures of alignment and imagination. In the overall workshops, which included different interactive tools, dialog quality (an indicator of the conditions for social learning) and reported learning (an indicator of the occurrence of learning) were correlated positively with alignment and imagination. While these constructs should be measured more robustly (e.g. with additional Likert items to construct more robust scales), this exploratory, proto-experimental research suggests a number of conclusions.

Participants rated CoAXs highly along the dimensions of alignment and imagination, suggesting it has promise to support social learning. For individual use of the CoAXs tool, these dimensions were negatively correlated with localization (*LFocus*) and adjustment based on personal experience (*RefExp*), an unexpected result perhaps related to skeptical participants who used personal experience to criticize the tool. Yet at the group level, testing more points of interest (*LFocusAvg*) was positively correlated with alignment and imagination, suggesting that broader social learning was enabled by the ability to test and compare accessibility impacts from different locations relevant to different users. Deliberation about impacts and questioning the tool itself, enabled by the speed and ease of comparing different points through touching and gesturing at the map, also seemed effective in supporting social learning.

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Specific usability and individual interaction aspects (touchscreen sensitivity, non-intuitive control of zooming) need further refinement through ongoing iterative testing. More fundamentally, the salience of accessibility impacts seemed to be skewed toward experts and not local residents. In addition, at least three less-engaged participants did not complete the exit survey, a noteworthy non-response bias.

The participants in these research workshops about relatively hypothetical corridors (i.e. proposed in an advocacy campaign but without clear prospects for implementation) were probably friendlier than typical planning meeting attendees. Concerns about representation in the larger sense are compounded by the finding that the tool was perceived to represent actual accessibility less accurately in underserved minority neighborhoods. So while CoAXs showed definite value as a PSS for targeted stakeholder engagement, prospects are more limited as a PGIS tool for broader audiences.

Incorporating ranges of service as actually operated (e.g. through archived vehicle location data and passenger travel times derived from smartcards instead of schedules alone) may be one way to build credibility and personal relevance of accessibility concepts for wider audiences, especially for neighborhoods with unreliable bus service and skeptical participants who are inclined to critique participation processes using the tool. The differing narratives about personalized experiences of access were a window into one of the core issues Sheller (2015) identifies: "how different social actors use narratives to frame transportation issues" (p. 14). Further research along this line of inquiry may show how framing the network impacts of transport in terms of access and accessibility can illuminate broader issues of race, power, and representation in transport planning.

While the preceding analysis offers suggestive findings, generalizability is limited at this stage. Larger sample sizes might enable sophisticated hierarchical models of individual-group interaction, but even decisions about large-scale projects often "reflect consensuses developed through deliberation in small, mixed groups," (Sagaris, 2016, p. 120), limiting the prospects for large-sample evaluations.

Compiling the measures of interaction used here (e.g. Table 4.2) for a typical public workshop or hearing would likely show major differences from the CoAXs-based engagement. Even if much work remains to realize and demonstrate the promise of such a tool for wide public involvement, it appears to be effective at this stage for collaborative stakeholder engagement in more targeted settings. Such engagement, in which the technical experts do not presume to know all benefits beforehand and instead rely on generating shared understandings about expanded access to opportunities with stakeholders, shows promise for fostering co-creation and making transport planning more aware of broader concerns and urban space.

Chapter 5

Experimental Workshops

Point-to-point time savings are often used to frame the benefits of transport projects when communicating with the public in abstract ways (see, for example, Figures 2.2 and 2.3). This chapter argues that an accessibility framing is more productive for stakeholder engagement than the typical time savings framing.

Building on the research discussed in the preceding chapter, a second round of workshops was conducted in October, 2016, in partnership with a Boston-area advocacy group. These workshops used two different versions of CoAXs, in an experimental setup designed to isolate the effect of the underlying concept of accessibility from the device, facilitation, and context factors confounded in the previous round of workshops. In addition to the accessibility-based version, a version showing point-to-point travel times helped control for the features of interactive mapping tools generally, independent of accessibility concepts.

The first section of this chapter explains the hypotheses guiding this research. Section 5.2 provides greater detail on the experimental context and methodology. Section 5.3 summarizes results and is followed by an analysis section and a discussion of lessons learned.

5.1 Hypotheses

Using two versions of CoAXs, the workshops tested two sets of hypotheses:

1. CoAXs broadens the scope of impacts considered, as revealed by shifts away from initial expectations of impacts on different groups. Rapid computation gives the ability to test many locations and input assumptions, which may help participants change their expectations through deliberation and exploration. Furthermore, it is hypothesized that the accessibility version will foster larger shifts than the point-to-point version, as it shows travel improvements to all potential destinations, rather than only one

destination.

2. CoAXs increases enthusiasm, a measure of advocacy intention for transit projects. While it is difficult to measure actual advocacy outcomes experimentally, enthusiasm for a project and a sense of capability in describing its features and impacts may be suitable proxies. As participants have more dynamic, personalized, and engaging media available to explore project impacts, they may be more enthusiastic about the project. An additional hypothesis is that the accessibility version of the tool fosters enthusiasm differently than the point-to-point version does.

5.2 Design and methodology

Four workshops were conducted, with notable differences in context, interface, and evaluation from the previous round of workshops.

5.2.1 Context: social and institutional setting

Each workshop had approximately ten participants recruited by the LivableStreets Alliance, an advocacy group in the Greater Boston area. Workshop agendas were developed in partnership with members of the LivableStreets advocacy committee (see Figure 5.1). These volunteers, along with LivableStreets staff, were eager to explore ways to build their members' enthusiasm beyond the organization's traditional core issues of walking, bicycling, and streetscape design. Such engagement was especially timely because of the state's upcoming long range transportation plan[1] and a recently completed study of bus priority measures. This study, commissioned by the Massachusetts Department of Transportation (MassDOT), identified corridors that might be good candidates for dedicated bus lanes or other priority measures based on high passenger volumes and low speeds[2]. Five of these corridor segments were selected as the focus of the experimental workshops (see Figure 5.2).

5.2.2 Intervention: underlying concepts, interface, and facilitation

Workshops lasted approximately two hours. In each workshop, participants listened to an overview of the MassDOT bus priority study and related projects, completed a pre-test survey, split into two groups, tested sample scenarios and their own modifications in one version of the tool, completed a post-test survey, and reconvened for a debrief discussion (see Figure 5.1). Two different touchscreens were used for the different tool versions, and participants were not informed until the end of the workshop that the groups had tested different versions.

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[1] https://www.mbtafocus40.com/

[2] https://www.massdot.state.ma.us/Portals/49/Docs/BusLane20160513%20.pdf

96
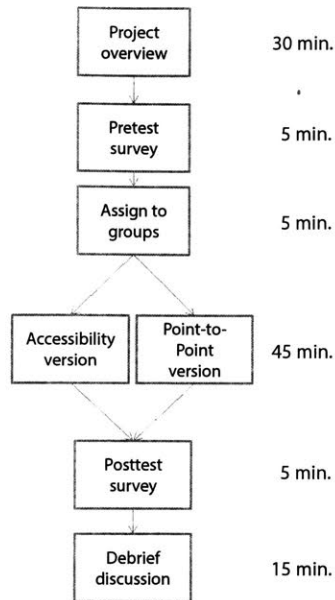
Figure 5.1: Flow of participants and information in experimental workshops

In addition to a team of observers and helpers, two primary facilitators were present, and between workshops they alternated between the tool versions. At a high level, use of both versions followed the five steps outlined in Figure 3.2. Participants spent the majority of the time comparing trips from different locations under different scenarios, through the lens of increased accessibility to jobs or decreased travel times. Using the notation introduced in Chapter 2, they tested multiple origins i, while mode M was fixed to walking and public transit, and T was fixed to 7-9 AM. In both versions, facilitators prompted participants to modify running time, dwell time, and frequency for the bus routes traversing each corridor segment (see Figure 5.2).

With the accessibility version, in addition to selecting an origin i, participants used a slider to specify a travel-time cutoff (5min. $\leq \tau \leq$ 120min.), then discussed the resulting isochrones and number of jobs reachable. Jobs were divided into three categories by wage level, as shown in the stacked bar charts of Figure 5.3.

With the point-to-point version, in addition to selecting an origin i, participants dragged a second map pin to specify a destination j, then discussed the resulting paths and required travel time. Travel time was divided into walking, waiting, and in-vehicle components, as shown in the stacked bar charts of Figure 5.4. Over the 120 minutes of the time window T, multiple paths between the origin and destination may be optimal, depending on departure time. The map showed the two paths that were most frequently optimal over T, while the bar chart displayed the median of the travel time components.

These two versions were designed to be as similar as possible in terms of user experience and interface, with the only differences tied to the underlying conceptual differences between travel time and accessibility representations of transport impacts.
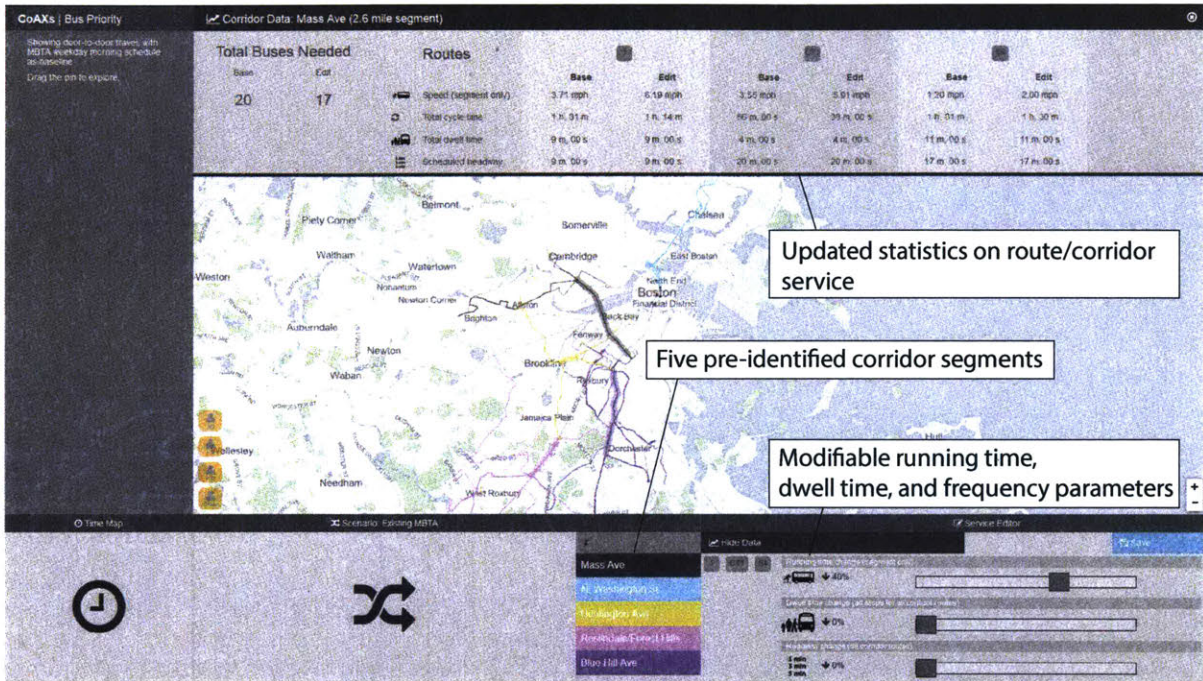
Figure 5.2: Scenario modification interface
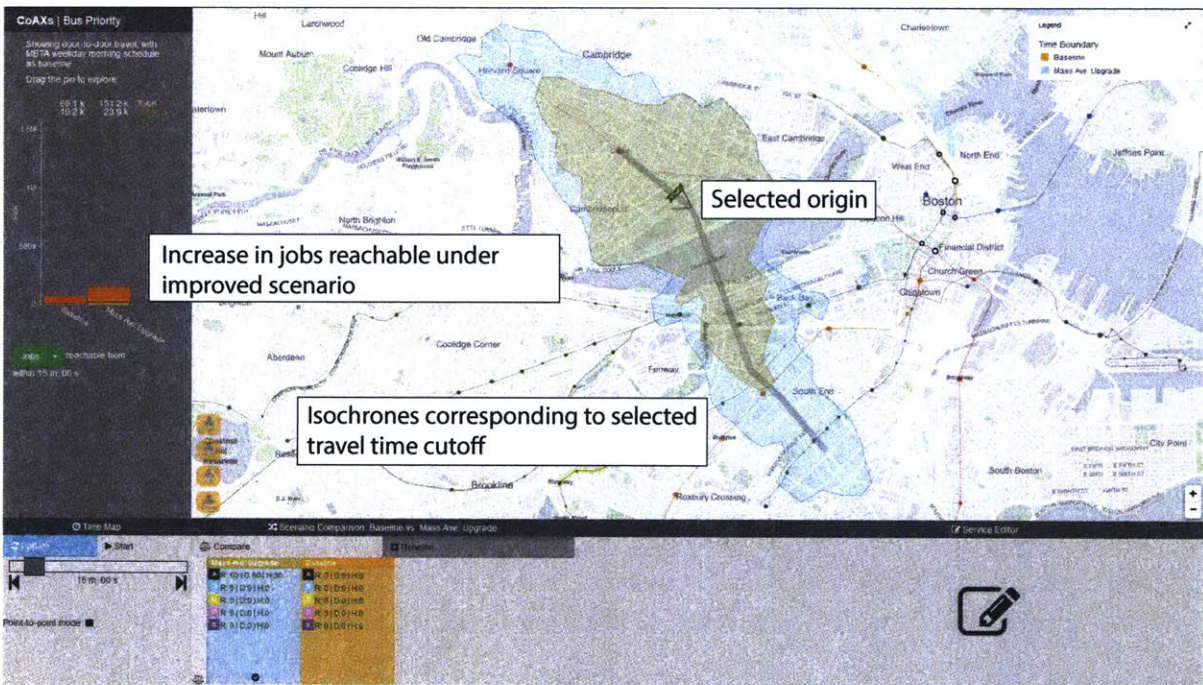
Figure 5.3: Accessibility version of CoAXs
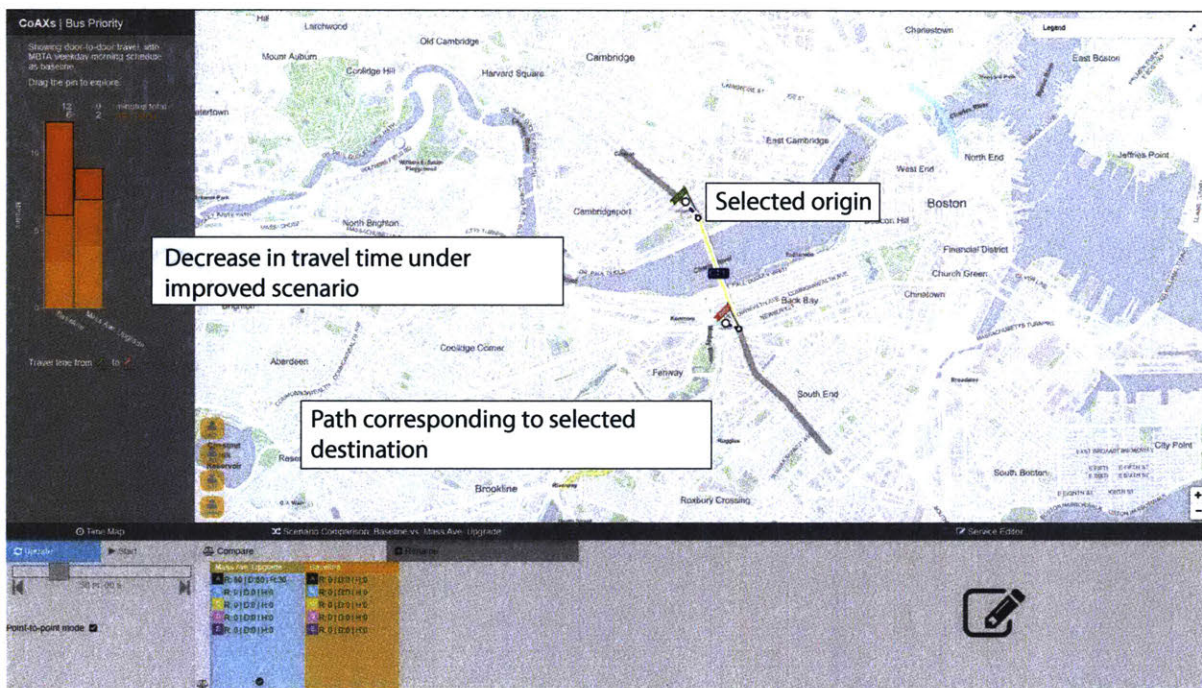
Figure 5.4: Point-to-point version of CoAXs

5.2.3 Outcomes and analysis techniques

The pre-test survey contains questions on past participation in planning meetings and an open-response item about modes of travel regularly used. It also includes Likert-type questions about expected impacts of a sample bus priority project on different groups, and enthusiasm about the sample project. The post-test survey repeats these questions and includes additional questions about the potential usefulness of CoAXs in planning processes, its effectiveness in promoting group alignment, imagination and dialog, and its usability.

For the five-point ordinal Likert scales about impacts, numerical values may be less meaningful than the direction of shifts (positive or negative) between the pre-test and post-test. Tilted line-segment plots can effectively show shifts in individuals' scores between the pre-test and post-test (Bonate, 2000), as presented in Figures 5.8 to 5.10. For each version of the tool, the percentages of participants whose responses indicated positive shifts, no shift, and negative shifts, are tabulated. A Wilcoxon rank-sum W test is also conducted, with the null hypothesis that the median response did not shift.

Fisher's Exact test is used to test the null hypothesis that the distribution of participants among the three shift categories (positive, none, and negative) is equal between the two versions of the tool. This approach is overly conservative, as its treatment of the categories ignores the meaningful ordinal differences between them (e.g. positive is greater than negative). Finally, Mann-Whitney U tests are used to test the null hypotheses that the distribution of pre-test scores is identical between the two versions of the tool and that the distribution of the post-test scores is identical between the two versions of the tool. An insignificant p-value for the pre-test scores, combined with a highly significant p-value for the post-test scores, would suggest that the participants had identically distributed scores in the pre-test (as would be expected given the random assignment of participants to tool versions) but differently distributed scores in the post-test, implying a difference in the effect of the two versions of the tool.

For the second set of hypotheses, an *enthusiasm* index is constructed for both the pre- and post-tests as the sum of three five-point Likert items [3]:

1. This project will be effective at advancing important transportation goals.

2. This project will help advance important broader urban goals (e.g. housing, education).

3. I am more likely to advocate for this project than other projects LivableStreets supports.

Enthusiasm scores on the post-test are the dependent variable in a set of ordinary-least-squares regression models (see Table 5.1). Various explanatory variables are tested:

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[3] 1 = strongly disagree to 5 = strongly agree

Enthu(pre)   It is obviously expected that participants' pre-test enthusiasm scores will correlate positively with their post-test enthusiasm scores.

Skept(pre)   Skepticism, as imputed from the pre-test questions about past planning meeting attendance, is expected to correlate negatively with enthusiasm.

Car(pre)   This binary variable was constructed from pre-test open-response items about regularly used modes. For a bus priority project, it is expected that enthusiasm will be lower for participants who report using cars.

Bus(pre)   Like the previous variable, this is a binary variable constructed from the pre-test open-response items about regularly used modes. For a bus priority project, it is expected that enthusiasm will be higher for participants who report using buses.

Self(post-pre) Participants who come to realize that a project will benefit them in unexpected ways are likely to be more enthusiastic about that project; the change in expected impact on one's self was accordingly tested as an explanatory variable.

Others(post)   Response to the question item "CoAXs helped me imagine what travel is like for others." Participants may be more enthusiastic the more tools help them empathize with others.

Own(post)   Regarding deliberation, participants may be more enthusiastic the more tools help them think about others' travel rather than their own. If strong deliberative effects hold, the estimated coefficients of *Others*(post) may be positive and the coefficients of *Own*(post) may be negative.

Dialog(post)   Participants who rate dialog quality highly would be expected to be more enthusiastic.

5.3   Results

In total, 37 people recruited by LivableStreets participated in the workshops, of whom 33 completed both surveys. The size of the groups within each workshop ranged from 3 to 6 participants. The results and analysis that follow draw on the survey data, as well as feedback from debrief discussions.

There was broad agreement that both versions of the tool support teamwork and meaningful conversation. As shown in Figure 5.5, well over 75% of participants were in agreement, and no participants disagreed, that "CoAXs provided a useful common ground for all of us to work together" and "CoAXs helped raise important issues for discussion."

A majority of participants were also in agreement that "if CoAXs were widely used in the planning process, it would support the kinds of conversations that the public needs to have about transport," but this agreement was less strong for the accessibility version than the

CoAXs provided a useful common ground for all of us to work together

CoAXs helped raise important issues for discussion
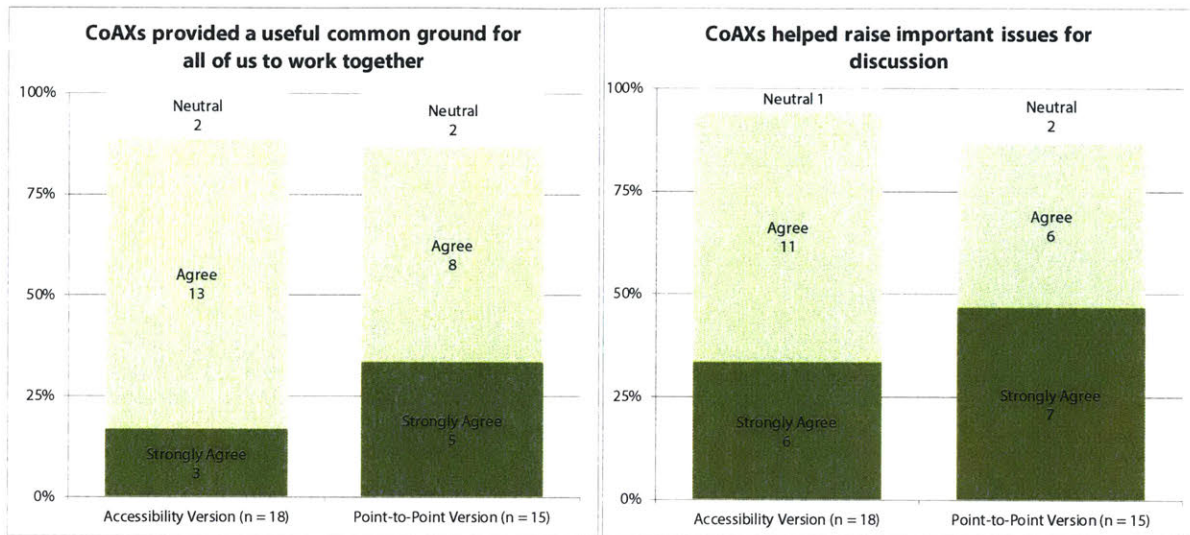
Figure 5.5: Distribution of survey responses - group alignment

point-to-point version (see Figure 5.6). Participants voiced concerns about the assumptions behind the tool that facilitators needed to explain, particularly for the accessibility version. For example, a user of the accessibility version was circumspect about the difficulty of "explaining the assumptions to an inherently skeptical community."

CoAXs, especially the accessibility version, prompted participants to imagine trips beyond their own. As shown in Figure 5.7, a substantial share of participants disagreed that the tool prompted them to think about their own travel, while strong majorities agreed that it helped them "imagine what travel is like for others." A point-to-point version user described experiencing "an ability to empathize with people and trips I wouldn't usually take." While this focus on broader impacts and empathizing with other travelers might be less fitting for typical public open houses in which members of the general public want to know specifically how a project would benefit themselves, it was seen as potentially useful for advocates targeting key decision-makers. This comment from an accessibility version user is telling: "If you're an advocate, you're not just thinking about your routes or your region or your sub-region, you're becoming more conversant in all the routes."

On a standard System Usability Scale[4], the accessibility version received an average rating of 57, and the point-to-point version received a significantly higher ($p = .01$ in a two-sided Student's t test) rating of 70.

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[4]https://www.usability.gov/how-to-and-tools/resources/templates/
system-usability-scale-sus.html
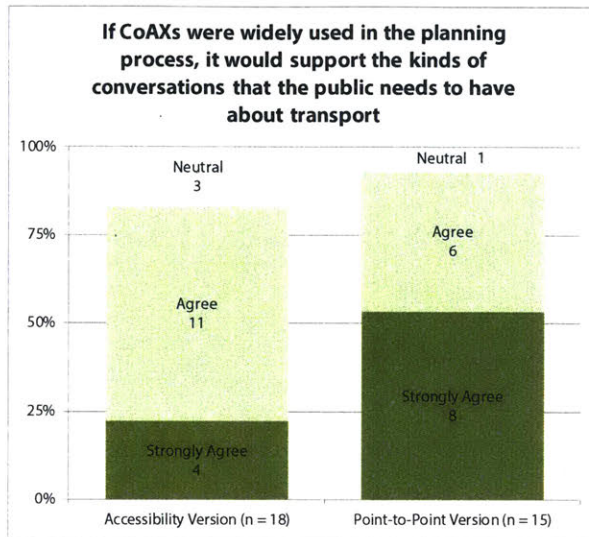
Figure 5.6: Distribution of survey responses - usefulness in planning
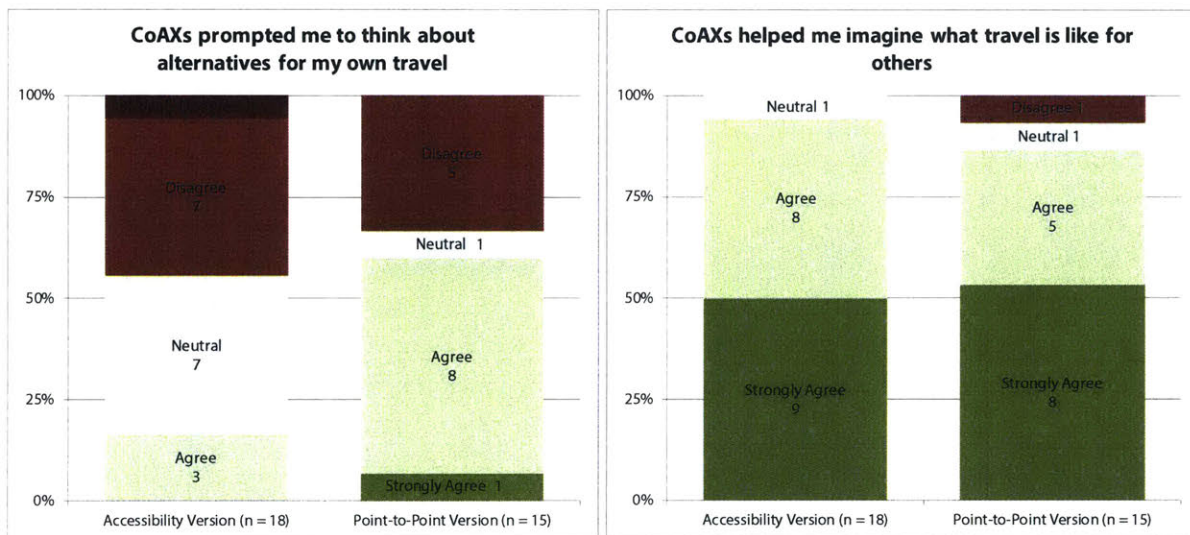
Figure 5.7: Distribution of survey responses - empathy

5.4 Analysis and discussion

The discussion below follows the hypotheses laid out in Section 5.1.

5.4.1 Broadened scope of impacts

Pre-test survey results show that participants tended to have initial expectations of significant positive impacts on transit riders and themselves, and of significant negative impacts on drivers (see Figures 5.8, 5.9 and 5.10). In many cases, shifts from the pre- to post- test suggest that these baseline expectations were not met.
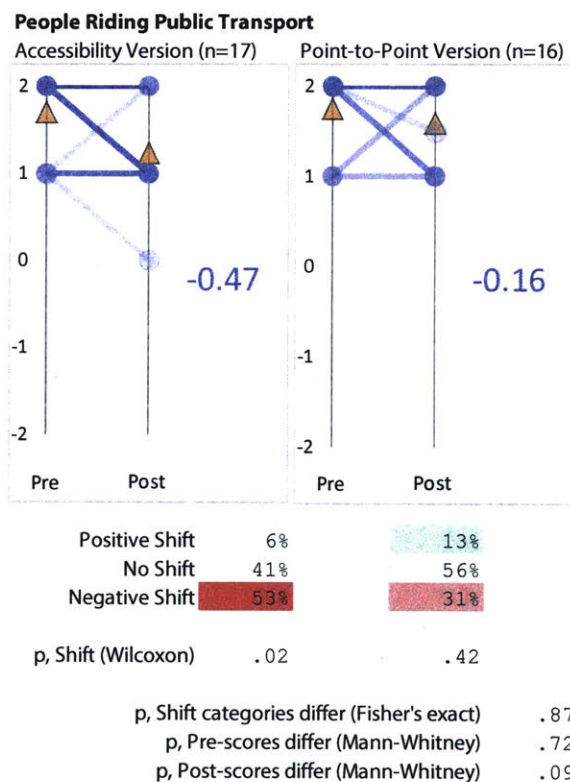
Figure 5.8: Shifts in expected impacts of bus priority on transit riders

Figure 5.8 summarizes responses to the question "how do you expect bus priority in the five corridors identified will impact people riding public transport?" In the pre-test, users of the accessibility version had a mean pre-test value[5] of 1.71, while users of the point-to-point version had a mean test value of 1.75 (denoted by the orange triangles). As expected, there is no evidence to reject the null hypothesis that the pre-test score distributions are the same ($p = .72$ in the Mann-Whitney test). Of the participants who used the accessibility version,

[5]On the adjusted scale of -2 = significant negative impact to +2 = significant positive impact

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a majority (53%) indicated a negative shift (a lower score on the post-test than on the pre-test), while the corresponding value for participants who used the point-to-point version was 31%. The mean value for the accessibility version decreased by 0.47, while the mean value for the point-to-point version decreased by 0.16. While comparing means of ordinal scales is of questionable validity, the Mann-Whitney results support the conclusion that the two versions had significantly different effects on participants' expected impacts; the pre-test scores were not significantly different, but the post-test scores were ($p = .09$).

Given the small sample sizes and idiosyncrasies of the experiment, these results should be interpreted with caution. The downward shifts may suggest disappointment when a fairly limited set of bus priority interventions failed to meet unrealistically high expectations of impact on transit riders. This grounding of expectations is probably attributable in part to the abbreviated nature of the overview of the five corridors that participants received before taking the pre-test survey. In this overview, the level of investment was not well-specified; participants likely imagined a set of aggressive interventions, whereas after deliberating in groups about modifying service parameters to create their own scenarios, the transit priority measures considered were much less ambitious.

It is not clear whether the significant negative shift ($p = .02$ in the Wilcoxon signed-ranks test) for the accessibility version makes it more closely approximate a "true" level of impact on transit riders. But to the extent that this negative shift is away from a naïve initial expectation that transit priority will have a significant positive impact on transit riders, the accessibility version may do a better job of prompting participants to think more realistically and holistically about impacts.

Figure 5.9 summarizes responses to questions about impacts on participants themselves, and their neighborhoods. The accessibility version had a negligible effect on participants' expected impacts on themselves. In contrast, 31% (5/16) of the point-to-point version users indicated a negative shift (with $p = .12$ in the Wilcoxon test for the shift). A similar pattern emerges for expected neighborhood impacts, with 25% (4/16) of participants indicating a negative shift. But the difference in pre-test neighborhood impact scores between the two versions suggests there may have been wide variability in the neighborhoods represented by participants, and how "neighborhood" was interpreted, limiting the validity of comparisons using this level of impact.

Similar trends were seen in responses to questions about bus priority projects' impact on people walking and driving (see Figure 5.10). For walking, users of the accessibility version ended up with significantly higher post-test scores than users of the point-to-point version ($p = .08$ in the Mann-Whitney test), likely due to the negative shift ($p = .07$ in the Wilcoxon test) associated with the point-to-point version. Anecdotally, this strong negative shift may be attributable partly to the way the components of median travel time were calculated and displayed; in some instances, optimal trips involved longer walking times, but shorter total times (e.g. if the total trip duration was shorter in a new scenario, but only if passengers walked to a more distant stop with faster transit service). This counterintuitive routing may have colored participants' expectations about impacts on people walking.

Yourself

Accessibility Version (n=17)	Point-to-Point Version (n=16)
0.00	-0.31

Your Neighborhood

Accessibility Version (n=17)	Point-to-Point Version (n=16)
+0.12	-0.13

	Accessibility	Point-to-Point			Accessibility	Point-to-Point
Positive Shift	6%	6%		Positive Shift	24%	13%
No Shift	88%	63%		No Shift	65%	63%
Negative Shift	6%	31%		Negative Shift	12%	25%
p, Shift (Wilcoxon)	1.00	.12		p, Shift (Wilcoxon)	.48	.48

p, Shift categories differ (Fisher's exact)	.13	p, Shift categories differ (Fisher's exact)	.55
p, Pre-scores differ (Mann-Whitney)	.38	p, Pre-scores differ (Mann-Whitney)	.21
p, Post-scores differ (Mann-Whitney)	.45	p, Post-scores differ (Mann-Whitney)	.01

Figure 5.9: Shifts in expected personal impacts of bus priority

For driving, the accessibility version saw a negative shift for only 6% of users, while the point-to-point version saw a negative shift for 25% of users. While there is not strong statistical evidence of a difference between the two versions in this case, a difference would not be unexpected given differences in the overarching directions of the conversations. Groups using the accessibility version deliberated about longer-term wider impacts and changes in travel behavior (e.g. mode shift from cars to transit), while the discussions of groups using the point-to-point version tended to be more limited to the corridors considered. The latter's focus would naturally prompt greater concern about right-of-way limitations and how bus lanes might delay drivers in the short term.

On balance, the accessibility version led expected impact on modes other than transit to shift upward, while the point-to-point version led expected impact on these modes to shift downward. It is important to reiterate here that CoAXs performs a *ceteris paribus* analysis of changes to the transit system; follow-on changes to traffic, land-use patterns, mode split, etc., are not modeled or represented. Participants' expectations about impacts on other modes are based on intuition and iterative exploration of first-order transit service changes, and these expectations may not be realistic. It is beyond the scope of this analysis to predict the "true" value of impact on pedestrians or drivers or how closely expectations align with predictions based on validated models. But to the extent that a positive shift in impact on drivers is away from a naïve baseline expectation that transit priority projects will negatively

People Walking

Accessibility Version (n=17)   Point-to-Point Version (n=16)

+0.13   -0.38

Pre   Post   Pre   Post

Positive Shift	25%	6%
No Shift	56%	56%
Negative Shift	19%	38%

p, Shift (Wilcoxon)   .58   .07

p, Shift categories differ (Fisher's exact)	.31
p, Pre-scores differ (Mann-Whitney)	.87
p, Post-scores differ (Mann-Whitney)	.08

People Driving

Accessibility Version (n=17)   Point-to-Point Version (n=16)

+0.24   0.00

Pre   Post   Pre   Post

Positive Shift	24%	19%
No Shift	71%	56%
Negative Shift	6%	25%

p, Shift (Wilcoxon)   .20   1.00

p, Shift categories differ (Fisher's exact)	.37
p, Pre-scores differ (Mann-Whitney)	.78
p, Post-scores differ (Mann-Whitney)	.77

Figure 5.10: Shifts in expected impacts of bus priority on users of other modes

impact drivers by reducing space for cars, the accessibility version may do a better job of broadening the scope of impacts considered.

5.4.2   Increased enthusiasm for public transport projects

The post-test *enthusiasm* index, with possible values from 3 to 15, had high internal consistency (Cronbach's $\alpha = 0.79$). Figure 5.11 shows participants' shifts in the enthusiasm score. Clear differences between the two versions of CoAXs are not readily discernible in this basic descriptive analysis. Diverging and highly heterogeneous responses were observed. The more familiar people become with a project, the more likely it is that they will have strong opinions for, or against, it, as shown by the increased ranges of enthusiasm scores in the post-test.

Table 5.1 summarizes linear regression models tested to explain post-test enthusiasm, using the independent variables described above.

Model 1 tests variables representing participants' predispositions. As expected, *Skept* is negative and significant in this model ($p = .010$), and most of the other models. The signs of the coefficients for the modal binary variables (*Car* and *Bus*) align with expectations, but
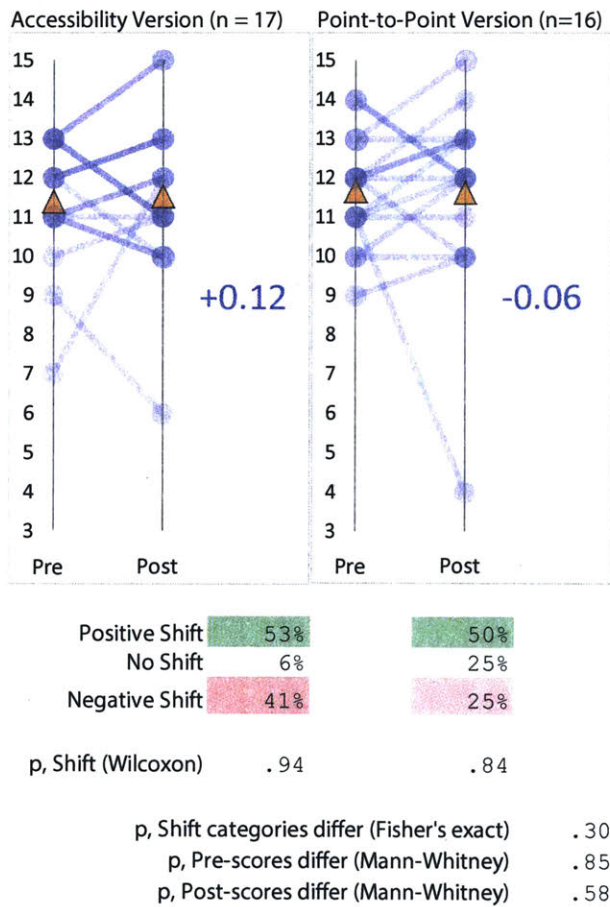
Figure 5.11: Shifts in *Enthusiasm*

they are not significant, and the overall explanatory power of the model is fairly weak (Adj. $R^2 = 0.32$).

Model 2 suggests that participants may be fairly myopic and do not gain enthusiasm from empathizing with others through the tools. *Self* and *Own* are positive and somewhat significant ($p = .075$ and $p = .074$ respectively), lending credence to the claim that these tools allow for effective personalization, while *Others* is not significant ($p = .980$).

Adding *Dialog* as an explanatory variable improves model fit (Adj. $R^2 = 0.84$) and the significance of most of the coefficients, as seen in Model 3. Unsurprisingly, higher ratings of a group's dialog quality correlate strongly and positively with enthusiasm for a project. Accounting for dialog quality makes *Others* negative and significant, a change from Model 2. This difference may suggest that exploring others' travel has mixed effects; it is valuable to structure dialog, but after controlling for quality dialog around testing locations relevant to other participants, participants would rather spend time exploring personally relevant origins and destinations. This finding aligns fairly well with the finding in the exploratory workshops that social learning was enabled by the ability to test and compare impacts from different locations (see Section 4.5).

Model 4 was estimated separately for users of the accessibility and point-to-point versions. The results of a Chow Test (F = 3.54 on 5 and 23 DF; $p = .016$) support this segmented estimation and the hypothesis that the accessibility version of the tool fosters enthusiasm differently than the point-to-point version does. For the point-to-point version (Model 4B), *Skept* dominates ($p = .006$), while *Car* and *Dialog* are moderately significant ($p = .113$ and $p = .111$ respectively). The reduced effect of *Enthu*(pre) in this model suggests that even participants who were initially enthusiastic about bus priority were likely to be dissuaded by the point-to-point version if they used cars or tended to be skeptical about participating in planning meetings. In contrast, for the accessibility version, the magnitude and significance ($p = .226$) of *Skept* in Model 4A are reduced compared to the preceding models. Model 4A also suggests the accessibility framing alleviates the predisposition of car users to be less enthusiastic about bus priority ($p = .962$ for *Car*(pre)).

The difference in the estimated effect of (*Dialog*(post)) between Model 4A and Model 4B is striking; dialog quality is a more important factor for predicting *Enthusiasm* when using the accessibility version than when using the point-to-point version. This finding aligns with anecdotal observations about the "relational spaces" fostered by the two tools. When using the point-to-point version, individuals testing their own trips of interest tended to stand in front of the screen, blocking it and testing different destinations with limited interaction with the other participants. In contrast, an individual using the accessibility version tended to move the origin marker to an origin of interest, then step back and discuss the resulting isochrones with the other participants; they would be more inclined to jump into a conversation referencing a representation of travel times that spans much of the region, rather than only a single trip with which they might not be familiar.

	Model 1 - "Predisposition"			Model 2 - "Myopia"			Model 3 - "Collaboration"		
	Coeff.	SE	p-val	Coeff.	SE	p-val	Coeff.	SE	p-val
Const.	5.40	2.63	.050 *	3.34	2.79	.242	-6.81	1.95	.002 **
Enthu (pre)	0.55	0.22	.019 *	0.56	0.24	.030 *	0.65	0.13	.000 **
Skept (pre, imputed)	-3.26	1.17	.010 **	-4.11	1.20	.002 **	-3.97	0.64	.000 **
Car (pre)	-0.53	0.71	.463	-0.73	0.69	.303	-1.00	0.37	.012 *
Bus (pre)	0.89	0.76	.251	1.38	0.76	.081 .	0.64	0.41	.137
Self (post-pre)				1.09	0.59	.075 .	0.98	0.31	.005 **
Own (post)				0.69	0.37	.074 .	0.79	0.20	.000 **
Others (post)				-0.01	0.53	.980	-0.82	0.30	.012 *
Dialog (post)							2.92	0.37	.000 **
n	33			32			32		
Adj. R^2	0.32			0.41			0.84		

	Model 4 - "Dialog"			Model 4A - Accessibility			Model 4B - Point-to-Point		
	Coeff.	SE	p-val	Coeff.	SE	p-val	Coeff.	SE	p-val
Const.	-3.71	2.84	.203	-8.61	3.84	.046 *	3.03	4.79	.541
Enthu (pre)	0.45	0.17	.013 *	0.59	0.21	.015 *	0.31	0.32	.349
Skept (pre, imputed)	-3.51	0.90	.001 ***	-1.83	1.43	.226	-4.09	1.19	.006 **
Car (pre)	-0.60	0.55	.286	-0.04	0.84	.962	-1.51	0.87	.113
Bus (pre)	0.43	0.59	.477	1.12	1.03	.301	0.10	0.83	.908
Dialog (post)	2.39	0.53	.000 ***	2.89	0.74	.002 **	1.40	0.80	.111
n	33			17			16		
Adj. R^2	0.60			0.63			0.65		

$** p < .01, * p < .05, . p < .10$

5.5 Lessons from experimental workshops

The preceding analysis suggests that relative to the point-to-point version, the accessibility version mitigated disappointment in the impacts of the interventions and prompted more attention to impacts on other users and modes, even though such impacts weren't explicitly modeled in either version of the tool.

There is tentative support for the first set of hypotheses: participants did shift away from naïve expectations of some impacts, and these shifts were often more pronounced for users of the accessibility version. The accessibility version was also deemed to foster greater focus on others' trips (as suggested in Figure 5.7), but this empathy did not seem to correlate directly with enthusiasm, even if dialog that it helped support did.

Regarding the second set of hypotheses, there were diverging responses, with some participants showing positive shifts in enthusiasm, and others showing negative shifts in enthusiasm. Many of the negative shifts reflect expectations about impacts of bus priority that were initially high and subsequently not met after using CoAXs. As one point-to-point version user put it, "After playing with the tool, I think I overestimated the positive impacts of these specific corridor improvements on transit users."

Three behavioral factors may help explain why more disappointment arose from groups using the point-to-point version. First, users could set and discuss prior expectations of impacts because the units of analysis (minutes) were familiar. In contrast, participants are unlikely to have a preconceived idea of how many jobs are accessible from a given location in the city, even if they are familiar with how long it takes to travel from that location to other points in the region. Users of the accessibility version were thus less likely to be disappointed because they were less likely to have initial expectations that were precise or subject to optimism bias. Second, the magnitude of the time savings changes (generally less than ten minutes) was smaller than the magnitude of accessibility changes (generally thousands of jobs). Combined with the first factor, people expecting large time savings are likely to be disappointed if the actual time savings are small. Third, the simple fact that time savings were represented as a decrease, while accessibility changes were represented as an increase, may bias perceptions. Future tests could test the impact of these behavioral factors by changing the metric of travel time changes (e.g. hours of relaxation gained per year due to shorter trips).

Overall, this chapter has shown evidence supporting the use of interactive accessibility maps in stakeholder engagement for transit projects. The regression estimates discussed in the previous section suggest that dialog differs substantially in its effect on enthusiasm depending on whether transit benefits are framed in terms of accessibility or travel time; future research could test models to explain more robust measures of dialog. A few additional cautions are warranted. Participants rated the point-to-point version significantly better in terms of usability, and there was stronger agreement about its ability to support public conversations about transport (see Figure 5.6). The former result is unsurprising, given strong similarities between the point-to-point version and familiar, widely used online trip-planning tools. The discrepancy in usefulness is somewhat more surprising, especially in light of the results of

the models shown in Table 5.1. The accessibility version better supported meaningful dialog and mitigated skeptical predispositions and modal biases, but perhaps its lower usability convinced participants that it would be less useful for wider public participation (see Te Brömmelstroet and Bertolini (2012)). It may also be the case that participants wanted to have their predispositions confirmed, and the cognitive dissonance of being challenged by deliberation and alternate framings of impacts made some people less inclined to agree with the tool's usefulness.

The preponderance of downward shifts in expected impacts deserves further attention. The survey instrument could be redesigned to reduce the effect of mean reversion – participants who responded with extreme values on the pre-test surveys could shift only toward less extreme values in the post-test. The project considered only a limited number and extent of corridor segments; impacts may have been more substantial, and responses may have been more enthusiastic, for a wider set of available interventions. Furthermore, the baseline levels of transit service represented in these versions of CoAXs may have been inflated. Because the tool showed scheduled, rather than actual, travel times and accessibility (e.g. it ignored congestion delays that impact many of the routes considered), important speed and reliability benefits of bus priority may have been overlooked, contributing to disappointment. A participant's comments in the debrief discussion highlights this issue:

> "One of the issues we came across was believability of the travel-time boundaries [isochrones] because of known congestion on those existing routes... It didn't feel very satisfying to tweak the levers and see the boundaries move only a block or two in some parts, but at the same time the initial time boundary didn't feel accurate."

This finding, on the importance of reliability and incorporating actual travel times, echoes one of the main lessons from Chapter 4. The next part of this dissertation considers improving the accuracy of accessibility metrics by incorporating congestion and other delays.

Part III

Constrained Accessibility Metrics

Chapter 6

Overview: Adjusting Accessibility Metrics

The stimulus of socio-spatial agglomeration is today being assertively described as the primary cause of economic development, technological innovation, and cultural creativity.

– Edward Soja
Seeking Spatial Justice, p. 14

Persons experiencing insufficient levels of accessibility...can rightfully make a claim on the wealth that is being generated by all members of society jointly for the improvement of their situation.

– Karel Martens
Transport Justice, p. 215

Typical cumulative-opportunity metrics are upper bounds of potential interaction, which may vastly exceed the amount of realized trip-making or a meaningful level of benefit. Downward adjustments are often needed to make such metrics meaningful, especially depending on the time horizon of benefits considered. This part of the dissertation considers how such adjustments might be incorporated into measures of employment and healthcare access.

Schultheis (2016) argues that the spatial and social factors of accessibility are entangled, but that past research has been siloed, considering the "spatial relationship between actual or potential service users and service providers" in isolation from "characteristics of the user population such as age, income or language [which] impact service usage" (p. 13). Accessibility analyses that focus on public transport and use disaggregate zones can break down some of these siloes; public transport is co-produced (Mohring (1972), Gebauer et al. (2010)) and often more deeply confounded with aspects of social identity than aggregate locational measures based simply on Euclidean distances. This fact makes analysis considering

detailed transit travel times, rather than distance alone, promising for implicitly including social characteristics.

The two sections that follow highlight accessibility differences between social groups. The third section of this chapter then reviews ways to adjust accessibility measures for reliability, matching and competition in opportunities, and transport capacity.

6.1 Labor markets and employment access

Cities reinforce learning and the accumulation of human capital by promoting interactions between diverse groups (Jacobs, 1961). Glaeser and Maré (2001) compare urban and rural areas and establish that urban areas have not only higher wage levels, but also higher wage growth. Glaeser and Resseger (2009) show that among metropolitan areas with highly-educated workforces, more populous areas have higher productivity. These findings suggest that denser urban environments enable faster learning, benefitting urban firms and workers. To the extent that variation in these benefits reflects differing levels of employment accessibility across different metropolitan areas, one might also expect these benefits to vary according to differences in accessibility within metropolitan areas, especially in ones large enough to exceed the size of typical commuting ranges.

This section elaborates on the role locational accessibility plays within metropolitan labor markets, which consist of workers who supply labor and firms that demand it. Commuting and transportation are fundamental to this market, yet "the literature on commuting leaves major gaps in the understanding of urban transportation problems" in part due to high levels of geographic aggregation that "conceal meaningful differences" between areas within cities (Shen, 2000, p. 68).

Discussing commuting in modern societies, Giddens (1984) cites the clustering of financial firms in the City of London as evidence of the reciprocal structuring of space and social patterns (p. 153). The remarkable commuting flows to this Square Mile, enabled by London's transport system, make it an apt example. During an average weekday morning, more than 1.2 million people enter central London between 7 and 10 AM (Transport for London, 2016). Bordering central London, the emerging financial hub of Canary Wharf and the Isle of Dogs (see Figure 7.7) sees a peak morning flow in excess of 60,000 commuters per hour (Transport for London, 2016). The reach and capacity of mass transport support a thick labor market[1] – one with large numbers of well-matched firms and workers – centered in local areas and with

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[1] The concept of labor market thickness should be distinguished here from market tightness. While the two may operate simultaneously, they are independent concepts, with the latter arguably more affected by macroeconomic variations than local transportation and spatial patterns. A tight market implies labor demand matches or exceeds supply, so job vacancy rates and starting wages will be relatively high, as firms compete for scarce workers. A slack market is characterized by the reverse – workers competing for scarce jobs with lower wages. Ihlanfeldt (1999) discusses labor market tightness in the context of ghettos in US cities, but this analysis presupposes poor transport links between ghetto and non-ghetto areas.

a global reputation. Advantages of thick labor markets include more productive worker-firm matches attributable to specialized employees and reduced risks of long unemployment or job vacancies (Moretti, 2011). These advantages are especially pertinent for industries that both experience excessive volatility and require workers with specialized skills, such as finance.

Space plays an important role in the operation of local labor markets, but not through simple geographic boundaries or mechanisms that are widely agreed upon in sociology, economics, geography, or urban studies literature (Fernandez and Su, 2004). Patterns of commuting and the clustering of firms offer a glimpse into how the transportation-enabled geographic distribution of economic and social relations "influences the nature of the social relations themselves, the divisions of labor, and the functions within them" (Massey, 1994, p. 23). Hanson and Pratt (1992) illustrate how employers in Central Massachusetts root firms in strategic locations "to win proximity to a local labor force having the particular characteristics deemed desirable"; in a similar manner, employees "contribute to carving out small-scale labor markets through a preference for short journeys to work, a reliance on personal contacts in finding jobs, and through residential rootedness in particular parts of the metropolitan area" (p. 373). These interconnected processes shape labor submarkets within metropolitan areas, delineated along jointly social and spatial lines. While (Peck, 1989) recognizes that land-use regulations, such as zoning, and transportation hubs structure local areas, he gives the latter little attention, despite the important role transport networks play in coordinating labor supply and demand across space within cities.

Economists have a long record of research on firm clustering, but thorough considerations of urban spatial intricacies were largely neglected in the mid- to late- 20th century, due in part to the lack of tractable models of imperfect competition (Krugman, 1998). Even as economists have turned their attention to "new economic geography" (Krugman, 1998), many of the complexities of space and transport have been glossed over. Studies of labor markets often focus on the firm perspective rather than the worker perspective (Herod, 1997); on distances or static travel times rather than dynamic ones[2]; and on comparisons of cities rather than analyses of different labor markets within cities. Mulley (2012) provides a thorough compilation of articles on urban form, accessibility, and economics, only a few of which consider the nuances of differing levels of transport service. In short, while operational characteristics of public transit matter a great deal in structuring labor markets, interactions between the two have been subject to relatively little attention in transportation and economics literature.

This part of the dissertation seeks to fill this research gap by developing accessibility metrics with high levels of spatial and temporal detail, and by demonstrating preliminary correlations between such metrics and broader policy interests. As a conceptual foundation, the following subsections about accessibility and labor markets trace two arguments. First, the *value* of accessibility may be underestimated if thick market effects are neglected. Subsections 6.1.1 and 6.1.2 discuss such effects from the perspective of firms and workers, respectively. Subsections 6.1.3 and 6.1.4 then describe ways in which a meaningful *level* of accessibility may be overstated if factors like labor market segmentation are not incorporated.

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[2]in the transportation literature, Graham (2007b) is a notable exception.

6.1.1 Firms benefit from thick labor markets enabled by transit

Positive feedback loops of agglomeration mechanisms help explain the correlation between firm clustering and productivity. A high effective density [3] of similar firms facilitates knowledge spillovers, shared facilities and intermediate suppliers, shared labor pools, and learning (Marshall (1890), Puga (2010), Alstadt et al. (2012)). Certain classes of firms enjoy especially high positive externalities from similar firms being located nearby, especially as the evolving knowledge economy places a higher value on face-to-face communication and information exchange relative to the exchange of material supplies. Puga (2010) summarizes recent research confirming the existence of these effects by showing that: clustering of productive activities occurs to a greater degree than would be expected if locations were random or caused by exogenous spatial factors, wages and rents are higher in dense urban environments, and direct measures of productivity vary spatially.

Public transport unlocks these firm agglomeration effects through its high capacity. Venables (2007) helped establish the *additionality* of agglomeration benefits of transport investments, over and above the time saving benefits traditionally included in cost-benefit analysis. In the UK, transport appraisal guidance now incorporates agglomeration benefits, calculated as the change in effective density multiplied by an empirically estimated elasticity of productivity with respect to effective density (DfT, 2014). In the US, project evaluation practice is much less advanced, but there may be opportunities to incorporate accessibility measures into the Federal Transit Administration New Starts process (Ducas, 2011) or MAP-21 performance measures. Chatman and Noland's (2014) detailed analysis of over 300 US metropolitan areas using Longitudinal Employer Household Dynamics data supports a strong positive relationship between transit service and wages, through the mechanism of employment density in central cities. They argue this approach is a useful refinement of previous studies of agglomeration, which have more aggregate units of analysis (e.g. entire metropolitan areas). Given firm agglomeration effects decay quickly over distance (Melo et al., 2016), high-capacity transit is essential to enabling the formation of local clusters with high effective densities of firms.

While transit's capacity enables firms to cluster and benefit from high effective densities, its reach also makes a wider pool of potential workers accessible. The larger the potential workforce accessible, the more productive matches are likely to be for a given level of search effort and recruitment costs (Wheaton and Lewis (2002), Moretti (2011)). Using both a model and empirical support, Wheeler (2001) argues that, assuming complementarity between firm capital and worker skill, thicker markets yield more productive matches, and this differentiation in productivity will generate variations in wages and expected return to learning and training. These variations between groups will in turn lead human capital to be unevenly distributed "across local geographic markets" (Wheeler, 2001, p. 881).

Current transport appraisal and project evaluation practice (see Weisbrod et al. (2009) for an

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[3]As noted previously, effective density is a special case of accessibility, where the origin and destination classes of opportunities are equivalent.

overview) may undervalue transit if it ignores these thick market effects. Typical measures of realized mobility, which assign a value to time saved for current and forecast trips, largely neglect the nature of the workers making these trips (see Rosewell (2012)). If a transport project increased the number of workers reachable and as a result, a worker is better suited to a job because her employer was able to select from a wider pool of potential employees, her productivity and value will be higher in ways that exceed the marginal decrement in time she spends at work due to a faster commute. Accessibility may be further undervalued if her employer invests in productivity-enhancing specialized equipment because of confidence in finding suitable employees. Martinez and Araya (2000) investigate land-use benefits and location externalities of transport, finding that evidence does not support the assumption that transport user benefits are fully capitalized into land rents. They recommend that "transport project appraisals should move towards land-use – transport integrated models to ensure global equilibrium conditions, which incorporates all access and technological location externalities" (p. 1623).

Thick-market effects may overlap substantially with the effective density of firms, but this is not necessarily the case. Firms in outlying locations, such as finance companies in Croydon south of London (see Figure 7.3), are illustrative. Given the steep distance decay of firm-to-firm agglomeration mechanisms (which rely on high levels of face-to-face interaction for knowledge spillovers, etc.), wider economic impacts of transport improvements for these firms may be underestimated if measured only in terms of effective density, as is current DfT practice; but firms would have high accessibility to workers in their specific industries, and thick market effects suggest this workforce accessibility may imply further wider economic impacts. In short, "the common practice in cost-benefit analysis, calculating travel time savings with fixed spatial distributions of activities, may lead to misjudged benefit estimations" (Geurs et al., 2012, p. 3).

6.1.2   Workers benefit from thick labor markets

Relative to firms' location decisions, the location decisions of workers have received little critical attention, despite their ability to "produce and manipulate geographic space" (Herod, 1997, p. 3). Residential location models tend to make simplistic assumptions about exogenous job locations and commuting costs (Waddell et al., 2007), ignoring the irregular geographic distributions of accessibility within regions.

Following Marshall (1890), consider a skilled worker of a certain industry who loses his job and lives in a location with access to few jobs in that industry. The longer he has to endure unemployment waiting for a well-matched position to become available, the more likely he is to switch industries, to one for which he is less suited and in which he will accordingly be less productive. This status would represent underemployment, as would taking a part-time job. Alternatively, he may move to a different location, which is likely to be costly. Given the risk of either outcome, his expected return on specialized training is diminished, making him less likely to pursue industry-specific training and stay in the industry even before the

loss of a job.

Accessibility plays a key role in mitigating these risks; within regions, zones with higher job accessibility, even using crude measures such as a ZIP code's share of metropolitan area jobs, tend to have lower unemployment durations (Dawkins et al., 2005). With accessibility to a large number of jobs in a given industry or occupation, a worker is more likely to invest in specialized training and, in the event of an exogenous job loss, more likely to find a new job without changing industries or occupations. Thicker labor markets reduce the cost of changing jobs within an occupational or industrial segment (Wheeler, 2001), and they reduce the rate of switching between occupations or industries; as a result, skills depreciate less quickly and wages grow more quickly (Bleakley and Lin, 2012). An exception to this pattern, which is nonetheless consistent with thick labor market mechanisms, is for young workers, who "take advantage of low search costs to search more intensively for the right occupational match" early in their careers (Bleakley and Lin, 2012, p. 88).

Depending on the time horizon chosen, the value of accessibility for a worker may differ. In the very short term, time savings for an existing commute predominate. On a cumulative plot of relevant opportunities reachable versus travel time, the vertical axis would have a maximum value of 1 – the one job to which a worker currently commutes. Accessibility to other jobs represents an option value that may be exercised in the event of a change in employer (see Laird et al. (2009) for a discussion of accessibility and option values). The above discussion on thick markets suggests that workers might realize part of this option value, even before any changes in employer, in the form of increased incentives for training and the attendant productivity and wage benefits. Furthermore, a residential location with access to many jobs reduces risk of having to pay substantial relocation or added commuting costs in the event of a change in employment, and such changes are becoming more common over the course of a worker's career (see Sullivan and Baruch (2009) for a review of the concepts of the protean/boundary-less career).

The increasing prevalence of dual-worker households compounds this issue. Discussing the co-location problem facing dual-career couples, Costa and Kahn (2000) note that the percentage of married couples in which both partners have college degrees tripled between 1960 and 1990. They conclude that larger cities are more attractive to such highly-educated couples because thicker labor markets make the co-location problem more tractable. By the same logic, within large metropolitan regions, residential locations with high accessibility to jobs should be more valuable with the growing tendencies for workers to change jobs over the course of their careers, and for households to have two highly-educated workers. The cumulative plot of opportunities relevant to a household, even in the near- to mid-term, should thus arguably have a maximum value much higher than the one or two jobs to which its residents currently commute.

Given these and other trends, such as declining rates of car use (see Delbosc (2016)), households would be expected to place an increasing premium on easy access by transit to many jobs, not just the jobs to which they currently commute. There is thus an argument to be made that the plot of relevant opportunities reachable should also include other jobs that

may not be immediate matches. Two other factors suggest that households may also value access to jobs beyond those similar to their current occupations, industries, and skill levels. Jobs may be a proxy for services and amenities, the reachability of which implies an option value. And in the long term, homeowners are likely to have a larger market of potential buyers, and fetch a higher price when they sell their home, if it is within easy reach of many jobs.

Like the preceding subsection, this subsection has argued that labor market thickness is increasingly valuable, and as a result, locations with high accessibility to jobs are increasingly valuable. In project evaluation, commuters' time savings accessing current jobs should be considered a lower bound, with actual benefits approaching an upper bound of access to all potential jobs (see also Foley (1974) on "latent opportunities"). As the information economy continues to take hold, the flow of knowledge, rather than concrete materials, grows more important; recognizing this, economists are calling for greater focus on human capital accumulation, and empirical evidence of the importance of matching in the market for highly specialized labor (Puga, 2010). While such work is largely outside the scope of transportation research, it may help confirm the increasing value of accessibility, which has important ramifications for the design and appraisal of transport infrastructure.

While the value of accessibility may be growing, a growing number people may not be able to take advantage of it. In the UK, 38% of jobseekers report that "lack of personal transport or poor public transport ... is a key barrier to getting a job" (Social Exclusion Unit, 2003, p. 2). Wilson (1996) and many others have detailed the overlapping social and spatial barriers to job access for the urban poor in the US and elsewhere. Jobs may be abundant and highly reachable by transit in cities, but intertwined barriers exist for poorer residents, a key contention of research on labor market segmentation (e.g. Reich et al. (1973)) and the spatial mismatch hypothesis (e.g. Kain (1992)).

6.1.3 Labor market segmentation

Critical geographers argue that job access is a complex process (Boschmann and Kwan, 2010). Boschmann's (2011) qualitative research about low-income workers suggests they are highly mobile in terms of daily commuting, as well as residential and employment arrangements; these workers lead "spatially transitory...lives frequently changing both jobs and residences" (p. 671). According to this analysis, residential location and job prospects are often dictated by changing transportation options. Golub et al. (2013) detail how transportation has reinforced legacies of discrimination in housing and job access in Oakland. In short, distance from work may play less of a role in job access than education, skills, and other social factors; yet as Bauder (2001) argues (citing Lefebvre (1991)), space still plays "a proactive role... in the segmentation of labor" (p. 38).

Labor markets are segmented by qualifications and wage levels into submarkets with limited crossover. Accessibility metrics should account for these divisions. Segmentation results from the strategic use of hierarchies, ethnic tensions, and other forces to create submarkets

"distinguished by different...characteristics and behavioral rules" (Reich et al., 1973, p. 359). At the extreme, this segmentation can be analyzed as a dual labor market, with a primary market for stable employment with high qualification requirements, barriers to entry, or unionization; and a secondary market distinguished by low wages, low returns to education and training, high turnover, and few channels for upward economic mobility (Peck (1989), Dickens and Lang (1993)). The secondary sector smooths capital accumulation, cultivating a large pool of labor that can be tapped flexibly in response to fluctuating markets.

Skeptics of dual market theory argue that it relies on economic models missing important links, and on the claim that participation in the secondary market actually diminishes workers' human capital, a claim which is difficult to support (Taubman and Wachter, 1986). In response, Dickens and Lang (1993) provide evidence showing segmentation is more extensive than would be expected from discrimination and age effects alone. They also cite studies using factor analysis of job characteristics to demonstrate segmentation, concluding, "many job characteristics are highly correlated" (p. 151). This high degree of correlation makes it difficult to choose a single dimension, whether industry, occupation, education qualifications, or wage, along which to define segmentation. Industries like finance and manufacturing tend to employ primary workers, and others like retail and services tend to employ secondary workers, but "industry is not a perfect proxy for segment, and neither is occupation" (Dickens and Lang, 1993, p. 147).

Segmentation and barriers to economic mobility may be reinforced spatially, but the extent to which they have clear geographic causes or manifestations is debatable. Brueckner et al. (2002) take the extreme position that workers' skills "govern" their residential locations; workers with low skills will be relegated to locations distant from employment, increasing the commuting costs they face. This conclusion aligns somewhat intuitively with the structure of developed cities in Australia (Currie et al., 2010) and Europe. But in the US, high-earning workers tend to reside in suburbs (with low job accessibility) to take advantage of other neighborhood amenities (Wang, 2003), a pattern which biases estimates of the effect of job access on employment downward (Ihlanfeldt and Sjoquist, 1998).

As metropolitan regions grow, they also grow more stratified in terms of wages and skills (Moretti (2011), Wheeler (2001)). While cities have always been marked by segregation, "a new form of differentiation appears to have emerged. Now a duality is common in cities (Mollonkopf and Castells, 1991)" (Golledge and Stimson, 1997, p. 143)[4].

Given this growing polarization, attention should be paid to both the upper and lower ends of the labor market. At the upper extreme, effective matching between highly specialized workers and jobs requires high levels of connectivity. And at the lower end, where poor

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[4]Perhaps ride-sourcing platforms established by transportation network companies exemplify this trend toward polarization. Ride-hailing through mobile phone applications enables high-income workers in the primary labor market to exercise new levels of on-demand mobility, facilitating face-to-face interactions. This extreme mobility is enabled by a surplus of workers in the secondary labor market, who face high degrees of instability in day-to-day routines, the uncertainty of opaque pricing and transaction mechanisms, high turnover, and few prospects for advancement. In a context of rampant dislocation and abstract space, location services dialectically become highly valued.

workers face high turnover rates and low pay, minimizing the costs of frequent searches for new "gigs" is important. High accessibility to employment may be of the most value at these low strata, despite (or because of) low monetary values of time.

6.1.4 Spatial mismatch hypothesis

The observation of Kain (1965) that firm locations were shifting away from inner cities in the US, while black families were less likely to move to suburban locations[5] and therefore more likely to endure chronic unemployment, framed the original terms of the "spatial mismatch" debate in the US. Various sides of the debate have emphasized locational and mobility perspectives on this mismatch (or the proximity and speed aspects, following Grengs et al. (2010)), and its ability to explain unemployment in minority communities (see Kain (1992), Ihlanfeldt and Sjoquist (1998), Preston and McLafferty (1999), and Fernandez and Su (2004) for reviews).

Both perspectives have tended to consider total employment[6] and to omit neighborhood effects. Much past research may "understate the true importance of job accessibility as a determinant of the relatively poor employment and earnings of minority workers" (Ihlanfeldt and Sjoquist, 1998, p. 880).

Case studies with higher geographic resolution

The spatial mismatch hypothesis has prompted informative research into segmentation (and segregation) in urban labor markets, but more refined intrametropolitan analyses than the initial distinction between inner cities and suburbs is needed (Preston and McLafferty, 1999). This need for higher degrees of geographic resolution is particularly acute as firms shift back toward central locations, as related concerns about gentrification and displacement in inner cities grow, and given the "considerable amount of local spatial variation in employment accessibility, especially for workers who commute by public transit" (Shen, 1998, p. 354).

Transportation's impact on job access of disadvantaged workers has received successive waves of attention in the US, with recent research partly in response to welfare reform in the 1990s (see Sanchez (2008) and Boschmann and Kwan (2010)). In most US regions, access to an automobile confers a strong advantage in job searches, but people in communities with the greatest need for extensive employment searches tend to have lower access to cars and be least able to bear high costs of car ownership (Taylor and Ong (1995), Wang (2003), Ong and Miller (2005), Shen (1998), Kawabata (2009)). Analyzing multi-modal accessibility data (at the TAZ level, aggregated to the PUMA level for joining with demographic data) for

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[5]Massey and Denton (1998) offer a detailed study of the impact of racial discrimination in housing

[6]For job seekers, job vacancies are more relevant than total number of jobs, but to the extent that vacancies arise from turnover rather than employment growth, the distribution of vacancies will follow the distribution of jobs (see Shen (2001))

the three-county Detroit region, Grengs (2010, p. 52) finds, "The inner-city actually offers substantial advantages in reaching jobs, with one major qualification: a worker needs a car." Pointing to this "automobile mismatch" in Los Angeles, Ong and Miller (2005, p. 53) argue that "transit availability is already high in many of the poorest neighborhoods" and recommend easing "access to cars among the poor."

Their recommendation is dubious given a number of limitations of their study. Their main job access measure is a function of the number of jobs within a three-mile radius of each tract, and they ignore spatial autocorrelation. Furthermore, their measure of transit availability, the raw capacity of bus service for each census tract, is analogous to a PTAL in that it ignores the destinations served by transit. While this formulation may be appropriate to construct an instrumental variable for auto ownership, it is inadequate as a measure of transit's value in connecting people to jobs; a tract could easily have many high-frequency bus routes that provide access to few jobs within reasonable commuting times, especially for a region as dispersed as Los Angeles[7]. As Grengs (2010, p. 52) writes, "To fix the urgent problem of poor access to jobs with public transit is to undo decades of choices that undermined public transit."

Employment matching

Within metropolitan areas, accessibility may have different effects on job access depending on neighborhood (see the regime-based spatial regression models in Boschmann and Kwan (2010)) and household income (Wang, 2003). Some studies motivated by the spatial mismatch hypothesis have accounted for labor market segmentation by matching workers and jobs in different classes of employment. These studies recognize that metrics that ignore differentiation between labor submarkets may obscure how accessibility operates differently for these submarkets.

Considering changes over a decade in accessibility of 100 randomly selected census tracts in the San Francisco Bay Area to five distinct occupational classes, Cervero et al. (1999) find that the executive, professional, and managerial class of employees had the highest levels of, and gains, in accessibility, while employees in service occupations had the lowest. They also calculate "accessibility advantages" that account for matching effects, subtracting the unmatched values from the matched values. Tracts with high median incomes, low unemployment, and few minorities tended to have positive accessibility advantage scores, while tracts with low median incomes, high unemployment, and many racial/ethnic minorities tended to have negative accessibility advantage scores. They conclude that the housing market more readily accommodates the housing preferences of high-income workers, and that race and education explain unemployment more strongly than employment accessibility, though their accessibility measure is based only on highway network distances and does not account for congested travel times or public transit options.

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[7]This situation might be caricaturized as having all the right buses to all the wrong places

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Golub and Martens (2014) calculate the distribution across the Bay Area population of access to service and manufacturing jobs by different modes for different proposed regional transportation plans. Shen (2001) considers accessibility to vacancies in low-skilled jobs in Boston, defined as jobs in sales, services, and labor-intensive occupations, and accounts for competition between transit and auto commuters. A related approach (considering the strong correlations between job characteristics discussed above) is to segment job access by wage or income levels (e.g. Shen (1998), Boschmann and Kwan (2010), Manaugh and El-Geneidy (2012)).

Grengs (2012) discusses the possibility of matching by wage or skill, but opts for presenting an accessibility index based on all jobs, and cumulative distributions of this index for households classified by income (see Figure 6.1). This representation is not unlike a Lorenz Curve, which Welch and Mishra (2013) construct in their development of a transit connectivity index for equity assessments.
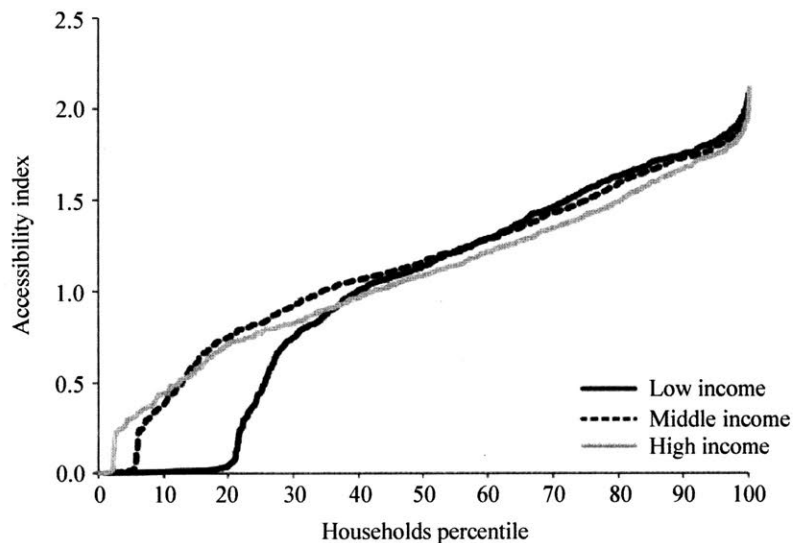
Figure 6.1: Accessibility to jobs in Detroit, by household type (Grengs, 2012)

Commuting time differentials

Other research has characterized spatial mismatch using commuting time differentials. This approach avoids the pitfalls of simple Euclidean distance-based measures, which may overlook how transportation makes destinations that are farther in space closer in time. Preston and McLafferty (1999) note that long commute times may represent higher commuting costs and barriers to job search, and that black workers have longer commutes than white workers, even controlling for wages, household and individual characteristics, and transport mode.

Shen (2000) uses 1990 CTPP data to analyze low-income clusters in central areas of the 20 largest US metropolitan areas and shows residents of these areas tend to have substantially longer commute times. Similarly, Williams et al. (2014) uses 2007-2011 ACS 5-year data to show substantial differences in commuting times between different racial groups of users of the same transport mode in Boston. While these findings support the spatial mismatch hypothesis, they are subject to a number of cautions. Commuting time differences between groups may be biased downward because of the sampling bias implied by excluding unemployed workers (Shen (1998, p. 359), Preston and McLafferty (1999)), and because minorities may be less likely to commute to distant jobs, because of limited transport options and limited social networks that may be less likely to inform them of these distant jobs (Ihlanfeldt and Sjoquist (1998, p. 856)). Self-reported average travel times may also ignore important variability in travel time.

6.2 Access to services

A focus on employment access alone may be too narrow in scope, missing wider overlapping patterns related to other trip purposes. Paget-Seekins (2012) confirms that a substantial proportion of transit trips in US cities, especially for low-income residents, are for non-work purposes. Bauder (2001) combines insights from labor market segmentation theory and cultural geography, maintaining that "labor market entrapment in secondary work often coincides with the spatial entrapment of women, minorities and low-income families" (p. 40). Massey and Denton (1998) is a foundational analysis of larger patterns of segregation and social exclusion in the US. Research in Europe has framed transport in terms of social exclusion, which "emphasizes the importance of a complex set of inter-related social processes (not just wealth creation)" (Hodgson and Turner, 2003, p. 266). Foley (1974) suggests planners should reconceptualize communities as spaces that share similar accessibility characteristics, instead of shared personal contacts and geographic continuity; this approach suggests that with growing social capital, wealth, and transportation options, residents are better "able to benefit from the potential array of opportunities open to them over and beyond the actual contacts to which they customarily travel" (p. 205). Hensher et al. (2014) connect such arguments to accessibility, arguing for the consideration of effective social density.

In the UK, the 2003 Social Exclusion Unit Report found that over 1.4 million people missed medical appointments or deferring medical care within the preceding year "because of transport problems" (Social Exclusion Unit, 2003, p. 2). The same report identifies five key barriers to accessing services (p. 3):

- Availability and physical accessibility of transport

- Cost of transport

- Services and activities located in inaccessible places

- Safety and security

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- Travel horizons - unwillingness to travel long distances, lack of knowledge or trust of transport services

Preston and Rajé (2007, p. 159) recognize the progress achieved by the Social Exclusion Unit in identifying these overlapping barriers, but they caution that "the resulting analysis may be too aggregate, both spatially and socially." Neutens (2015, p. 14) echoes this caution in the specific case of access to healthcare services, calling for more "spatially disaggregated, individualized and temporally-aware accessibility metrics, more sophisticated geocomputational tools to operationalize such metrics and improved measurement of equity considerations in empirical research." And as discussed in Chapter 2, participation in political decision-making should not be neglected in efforts to address social exclusion.

It is clear that many aspects of social exclusion are outside the scope of transportation. But transport providers must be able to explain clearly the access they promise and deliver (in settings that encourage meaningful participation, as discussed previously). An inability to articulate how the spatial and temporal nuances of transport render space plastic will impede efforts to address the overlapping layers of social exclusion that limit peoples' access to services.

6.3   Adjusting accessibility metrics for constraints

Without incorporating constraints that are meaningful to travelers' everyday behavior, accessibility metrics run the risk of becoming yet another abstraction of space that impedes meaningful participation. Various adjustments can reduce accessibility metrics downward toward meaningful levels of realized benefit. In the extreme, each traveler is constrained to match only one opportunity, collapsing accessibility into realized travel time. This section considers four downward adjustments to the core, maximum potential accessibility metric discussed in Chapter 2; for every origin of i, from $1...n$, of class O:

$$a_i(D, M, T) = \sum_{j=1}^{m} q_j(D) f(t_{ij}(M, T))$$

where:

D is the selected destination type (e.g. jobs, potential employees available)

M is the mode of travel (e.g. auto, transit)

T is a time window for the trip (e.g. peak, off-peak, which implies a certain pattern of service offered, congestion delays, etc.)

$q_j(D)$ is the attractiveness or number of opportunities of type D in zone j

$t_{ij}(M,T)$ is a representative (e.g. minimum, maximum, median, or mean) time or generalized cost to travel from zone i to zone j by mode M in time period T

$f(t)$ is an attractiveness decay function, generally returning decreasing values as the time or generalized cost argument t increases

Similarly, as discussed in Chapter 2, regional connectivity metrics A can be calculated for given origin classes O.

Four classes of adjustments to typical accessibility and connectiivyt metrics are proposed here, labeled A-D.

6.3.1   A: Adjusting impedance values for varying transport supply

Travel times and costs used in accessibility analysis should accurately represent the range of actual experience. While much has been written about how $t_{ij}(M,T)$ varies as a function of M (see Section 6.1.4, Black and Conroy (1977), Koenig (1980), Shen (1998), and Levinson and Kumar (1994)), comparatively little has been written about how it varies as T changes, over the course of a day, or between days.

For travel by car, this change is a fairly straightforward function of congestion, but even as the formulation of t_{ij} has evolved from Euclidean distances to network-based generalized costs, it is often the case that congestion-induced variability is ignored (Forer, 1978, p. 258). Cui and Levinson (2016) quantify the impact of unreliable roadway speeds, derived from the 10th and 90th percentile speeds of individual roadway links, on accessibility to jobs by car. Shen and Zhao (2017, p. 25) use a reported city-wide speed, the total length of five different road types, and the design speed of each road type to estimate assumed speeds for each link in the road network.

For public transit, t_{ij} depends on the intricacies of schedules, the "'small time' nuances of congestion, timetabling or fare-structuring that characterize transport" (Forer, 1978, p. 259). If a passenger just misses a scheduled service that runs infrequently, her experienced level of accessibility will be lower than expected. Traditional accessibility metrics using simple average headway miss this variability, though recent technical advancements have shown nuanced ways of accounting for temporal fluctuations within time windows of accessibility analysis (Fransen et al. (2015), Nassir et al. (2016), Conway et al. (2017)).

The first class of adjustments proposed here (class A) accounts for how t_{ij} in a given time window (e.g. the morning peak) may vary over the course of days or months. Instead of an accessibility value a_i^{sch} calculated using travel times $\bar{t}_{ij}$ based on scheduled service, inter-zone travel times feasible given actual operations (e.g. obtained by building a timetable for the network's services retrospectively based on archived vehicle tracking data) can be incorporated using one of two approaches.

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First, for each day $k \in K$, an accessibility value can be calculated and a conservatively low value of the a_i^k values can be chosen as a_i^{rel} (e.g. the minimum or 10th percentile). This reliability-adjusted accessibility figure represents service on a single day with poor performance and is readily explainable (e.g. the number of jobs reachable on a specific day), but it may inflate accessibility, especially if destinations of type D are not readily interchangeable and patterns of delay are not regular. For example, a job that happened to be reachable from a given origin on that origin's lowest accessibility day would be considered accessible even if it were not reachable on any of the other days in K.

An alternative is to select conservatively high (e.g. maximum or 90th percentile) value of t_{ij}^k (e.g. $a^{\text{rel}} = a(\max_k[t_{ij}^k])$). While this approach may be more closely aligned with the approach of Cui and Levinson (2016) and preferable in settings where congestion is highly irregular, it is less intuitive, as this version of a_i^{rel} represents a composite of different days, and performance on any single day might not be as degraded. Furthermore, this approach is more computationally intensive; because values of t_{ij} must be compared across days, storage requirements for a regional summary value of A grow on the order of nmK (or nm if only an extreme value of t is being considered), which may be intractable for a large number of origins compared to the nK requirement of the first approach.

The first approach is taken in Chapter 7, and the second is taken in Chapter 8. With either approach, the values of a can be used to represent both nonconformity with published schedules (e.g. the percent difference, $(a^{\text{sch}} - a^{\text{rel}})/a^{\text{sch}}$) and day-to-day service variability (e.g. the coefficient of variation of the values of a^k).

Both of these supply-side adjustments may underestimate how accessibility is actually diminished for customers, because they assume that customers have perfect foresight about future states of the network and adjust their path choices accordingly, rather than strategically in the context of limited information (see Cats (2011)). For day-to-day travel, passengers may be more concerned with reliability buffer time for a specific origin-destination pair than reliability-adjusted accessibility of their origin to all destinations. But from the larger planning perspective, and to the extent that actual accessibility is valued by households, the variability of connectivity A^k and the extent to which A^{rel} does not conform to A^{sch} should be of concern.

6.3.2 B: Adjusting opportunity values for matching constraints

In the near- and mid-term, only a subset of destinations, whether jobs requiring a certain level of skill or healthcare providers with a certain specialty, are likely to be relevant for certain classes of origin population O. Constraining connectivity metrics so that O and D are well-matched is the second class of adjustment considered here (class B). For example, for firms of class x,

$$A^{\text{matched}_x} = A(\text{jobs in class } x, \text{workers in class } x, M, T, C)$$

which reflects the extent to which workers in that employment class enhance labor market thickness by living in locations that are well connected to the firms of that class. If an unconstrained level of connectivity for these firms is denoted as

$$A^{\text{unmatched}_x} = A(\text{jobs in class } x, \text{all workers}, M, T, C)$$

then the connectivity advantage for firm class x can be calculated (following Cervero et al. (1999)):

$$A^{\text{Adv}} = \frac{(A^{\text{matched}} - A^{\text{unmatched}})}{A^{\text{unmatched}}}$$

Positive values of A^{Adv} imply, for example, that a firm's average matched potential worker resides within easier reach of the firm than the average of all workers in a region.

6.3.3   C: Opportunity competition

Accessibility metrics can also account for competition for rival opportunities. Building on Weibull (1976), Shen (1998) analyzes competition-adjusted accessibility to jobs in Boston. In this approach, each job is first normalized by how many workers can reach it, then accessibility to the normalized jobs is calculated. While central city residents are proximate to many jobs downtown, slow transit travel times to these jobs, compounded by the fact that many competing workers can access the jobs by both transit and auto, mean that transit-dependent central city residents may experience low levels of adjusted accessibility. Kawabata (2009), Grengs (2010), and Grengs (2012) apply similar two-step analyses to San Francisco and Detroit. In their study of welfare clients in the Chicago region, Thakuriah and Metaxatos (2000) adjust a basic 90-minute binary cutoff measure for the number of competing clients within the catchment of each job.

Van Wee et al. (2001) use a similar approach for the Netherlands, arguing that it should also incorporate a degree of recursion – the normalization of each job should account for the fact that the workers who can reach it can also reach other jobs, etc. They note that the proper degree of this recursion has not been established and test 0, 1, and 2 degrees for binary cutoff thresholds (τ) of 30, 45, 60, and 120 minutes. They find that with 0-degree recursion and using simple distance-based travel times (i.e. using the same approach as Shen (1998), but without different modes), competition-adjusted values of accessibility differ from unadjusted values by -5 % to over +10%. With additional degrees of recursion, they differ even more, suggesting competition may be important to consider.

Competition (class C) could also be expected to compound the effects of adjustments for reliability (class A). If auto travel times are more reliable than transit travel-times, then the competition- and reliability-adjusted access available to transit users would be degraded

because they are competing with more reliable workers.

Taken to its extreme, an attempt to represent opportunity competition turns into the doubly-constrained spatial interaction model that translates zonal production and attraction estimates into a matrix of O-D flows – the trip-distribution step of the traditional four-step model. Alternatively, agent-based simulation may be able to capture relevant capacity constraints in workplace choice (Vitins et al., 2016).

6.3.4   D: Transport capacity

To adjust accessibility values for capacity constraints across a network, full assignment models are generally needed. Intermediate approaches include Shen and Zhao (2017), who use queuing theory to calculate the mode splits between high-speed rail and cars for a pair of stations, as well as Nuzzolo et al. (2012) and Cats et al. (2016). If travel times that accurately reflect transport capacity are used as inputs to accessibility calculations, then the resulting accessibility metrics will be capacity-constrained. It can be hard to reconcile, however, a desire to understand all potential tripmaking with inputs that presuppose what trips are actually made.

Another option is to consider cordon capacities in the vicinity of highly centralized areas. In this option, peak load points of transit lines are assumed to be at the chosen cordon, i.e. that the entire network serves the area of analysis. The reach and capacity functions of transit are separated, but the perspective taken on capacity is limited, potentially too narrow to be of value.

6.4   Organization of empirical cases

This chapter has argued that while the value of urban accessibility is growing, properly measuring a meaningful level of accessibility requires the consideration of a range of constraints. Four classes of adjustments (A-D above) are proposed to reflect these constraints, and the next two chapters illustrate selected applications of these adjustments. These empirical cases contribute to existing research by showing how these different adjustments can be applied in ways that are straightforward, comprehensible, and easily computed for highly disaggregate geographies, building on the participatory foundation outlined in Part I of this dissertation.

Chapter 7

Constrained Employment Access

The geography of social structure is a geography of class relations, not just a map of social classes; just as the geography of the economy should be a map of economic relations stretched over space, and not just, for instance, a map of different types of jobs.

– Doreen Massey
Space, Place, and Gender, p. 22

As argued in Section 6.3, measures of access to employment should be constrained by how public transport actually operates and matching constraints in metropolitan labor markets. Workers, for example, presumably value access to jobs that are well matched to their skills and qualifications more than access to jobs that are not. This chapter seeks to characterize the effect of such constraints in Greater London. London is selected for this case study because of its high public transport mode share, its expansive size and specialization of labor, and its global reputation as an employment hub.

Public transport agencies provide a range of scheduled accessibility – accessibility based on promised service levels and scheduled travel times – across their service areas. This geographic variation is not undesirable, assuming land-use markets operate equitably and allow residents to live in locations that match their preferences. If this assumption about land-use markets does not hold, however, as may be the case given discrimination in the housing market (especially in the US; see Massey and Denton (1998), Gabriel and Rosenthal (1996)), strong correlations between unemployment and accessibility should be of concern to policy-makers, regardless of the direction of causality. Though relations between unemployment and access to jobs are complex and highly endogenous (Gao et al., 2008), if secondary-sector workers face both the greatest need to search for jobs due to high turnover, and the highest search costs due to low locational accessibility, the overall pattern of transport service provision may reinforce barriers to employment. Even if scheduled accessibility is distributed equitably, accessibility based on actually operated service may be inequitably provided.

7.1 Research question and hypotheses

How important is the reliability of actual accessibility, relative to scheduled or mean accessibility? And what biases might be introduced by considering unadjusted accessibility metrics that ignore matching between workers and jobs? Two sets of hypotheses structure responses to these questions. They draw on schedule nonconformity and service variability adjustments (class A of those discussed above), and matching constraints (class B discussed above).

7.1.1 Unemployment rates

In general, it is expected that accessibility to jobs will correlate negatively with rates of unemployment, but multiple causal mechanisms and confounding factors may play a role. If it is difficult to reach jobs from a certain neighborhood, that neighborhood's residents may be less likely to search for and find work, *ceteris paribus*, increasing unemployment rates. And people who tend to be unemployed may locate in lower-accessibility areas, playing lower housing costs due to lower willingness or ability to pay. On the other hand, if people tend to be unemployed and often need to search actively for work, they may locate in areas with high job accessibility to facilitate searches. Unemployed populations may also tend to cluster in more central areas for better access to amenities and social services, leading to positive correlations between unemployment and accessibility.

Two measures of the unreliability of accessibility to low-qualification jobs by bus during weekday mornings (8:00 to 8:30 over a span of four days) are tested here.

First, schedule nonconformity can be represented as the percent difference between scheduled and actual accessibility. It is expected that this measure of accessibility nonconformity, PD_a will correlate positively with unemployment rate; if a resident's actual level of access to jobs falls below the promised level (i.e. nonconformity is high), she is more likely to face transport reliability barriers to employment.

Second, service variability can be represented as a coefficient of variation (e.g. the standard deviation of a_i^k over each of the days k, divided by $mean_k[a_i^k]$). It is expected that service variability, COV_a, will correlate positively with unemployment rates; the less reliable a resident's access to jobs is, the less likely he is to be employed.

7.1.2 Connectivity advantage by employment class

It is expected that for employment classes that tend toward thick markets, such as finance and high-qualification jobs, connectivity advantage will be positive ($A^{Adv} > 0$, see subsection 6.3.2), while for other classes, such as low-qualification jobs, there will be a connectivity

disadvantage ($A^{\mathrm{Adv}} < 0$). These measures are calculated for scheduled weekday morning service, assuming a random departure between 8:00 and 8:30 using all available public transport modes (bus, Underground, Overground, National Rail, etc.).

Thick labor markets and measures of connectivity advantage were discussed in Chapter 6. It is expected that firms in volatile industries, such as finance, will need access to substantially thicker labor markets than firms in less volatile industries like healthcare. It is also expected that connectivity between workers and jobs with high levels of formal education will be higher than connectivity between less-qualified workers and jobs. This is a jointly-determined problem, which can be viewed from the perspective of workers or firms. Using the notation defined in Section 6.3.2, this can be decomposed into a matched and unmatched connectivity, which can be used to calculate a connectivity advantage (A^{Adv}).

7.2 Data

Socioeconomic data or home and work locations are from the UK Office of National Statistics (ONS) Census 2011, as described in 7.2.1. Transport data are from timetables for TfL and National Rail services, as well as from a database of archived automatic vehicle location (AVL) data for London Buses, as described in 7.2.2.

7.2.1 Demographic data

From ONS Census 2011, tables summarizing attributes of working-age (16-74 years old) residents at the output-area level include:

- method of travel to work (QS701EW)

- economic activity (QS601EW) – whether residents are economically active (employed full-time, employed part-time, self-employed, full-time student, or unemployed) or not economically active (retired, student, looking after home or family, long-term sick or disabled, or other)

- worker's industry according to a 26-category breakdown following the UK Standard Industrial Classification 2007 (QS605EW)

- resident's highest level of qualification (QS501EW), grouped into the categories of None, Level 1, Level 2 (e.g, basic high school), Apprenticeship, Level 3 (e.g A level), Level 4 (e.g. certificate of higher education) and above, and Other.

- ethnic group (KS201EW) (for all usual residents, rather than only working-age residents)
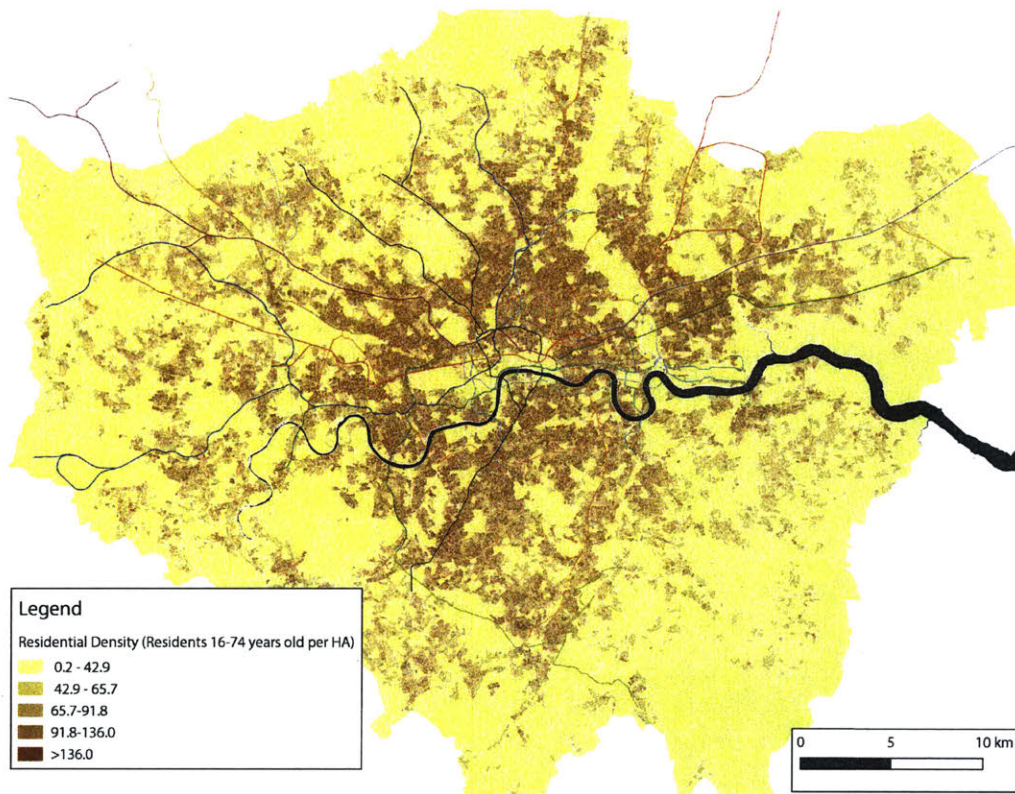
Figure 7.1: Greater London workforce density, residents 16-74 years old (Data: ONS [Census 2011, QS701EW])

Select demographic data from these tables, for the 25,053 output areas in Greater London, are mapped in Figures 7.1 to 7.5 and summarized in Table 7.1. The boundaries of output areas are defined so that each includes at least 40 resident households, a confidentiality threshold.

Similar data for place of work were compiled, using a set of 9,250 Census 2011 work areas roughly bounded by the M25 beltway. Job data reflect the characteristics of the current job-holders. For example, a job would be classified as Level 4 qualification if currently held by a worker with that level, even if the firm would be willing to hire someone with only Level 1 qualification for the position.

Figure 7.2 shows notable clusters of unemployment to the east and northeast of London.

Figure 7.3 shows the density of workers in the finance industry, concentrated in the City and Canary Wharf, with some outlying clusters in areas like Croydon.

Figure 7.4 shows the density of healthcare workers, who are much more evenly distributed across Greater London. This dispersion is expected, given that healthcare facilities are located to be proximate to residential populations. The attractive pull of potential patients has a dispersing effect, as opposed to the agglomerative pull experienced by finance firms
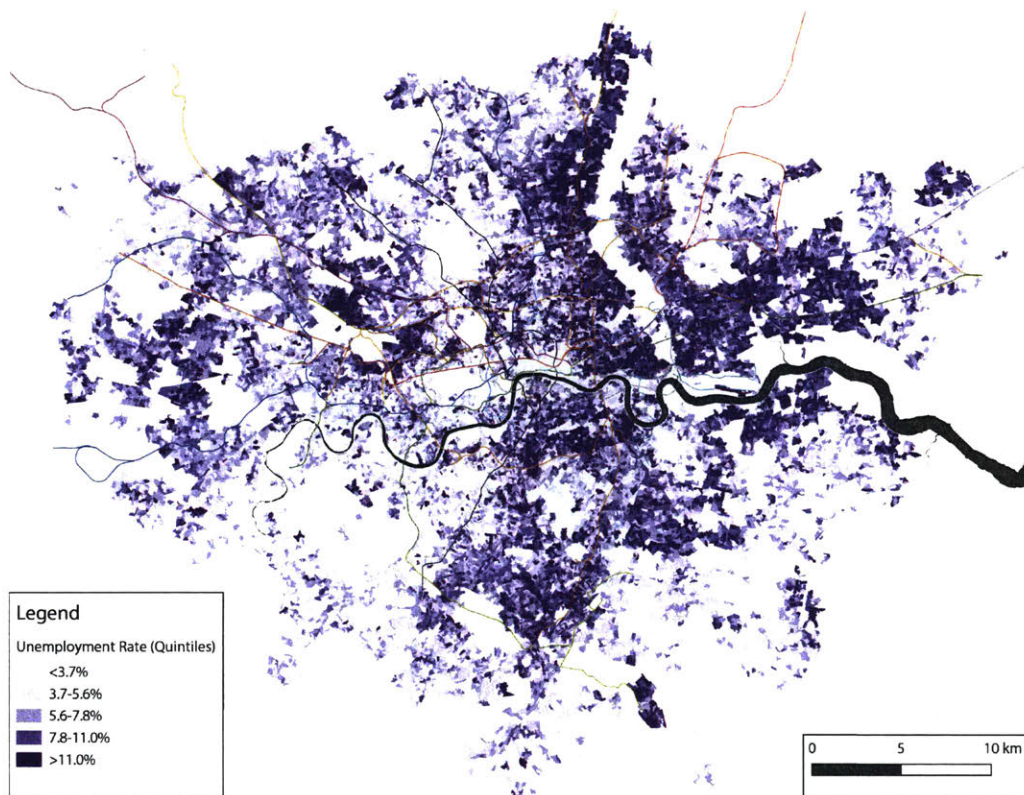
Figure 7.2: Greater London unemployment rate, by output area with density at least 5 residents per hectare (Data: ONS [Census 2011, QS701EW])

seeking high effective densities.

Figure 7.5 shows the density of residents and workers with highest level of qualification reported as None or Level 1 (referred to hereafter as low-qualification). The residential density of these workers corresponds somewhat, at least visually, to rates of unemployment.

Legend

Residential Density (Finance workers per HA)
- 0-4
- 4-8
- 8-16
- 16-32
- >32

a) by residence location

Legend

Job Density (Finance Jobs per HA)
- 0-2
- 2-4
- 4-8
- 8-16
- >16
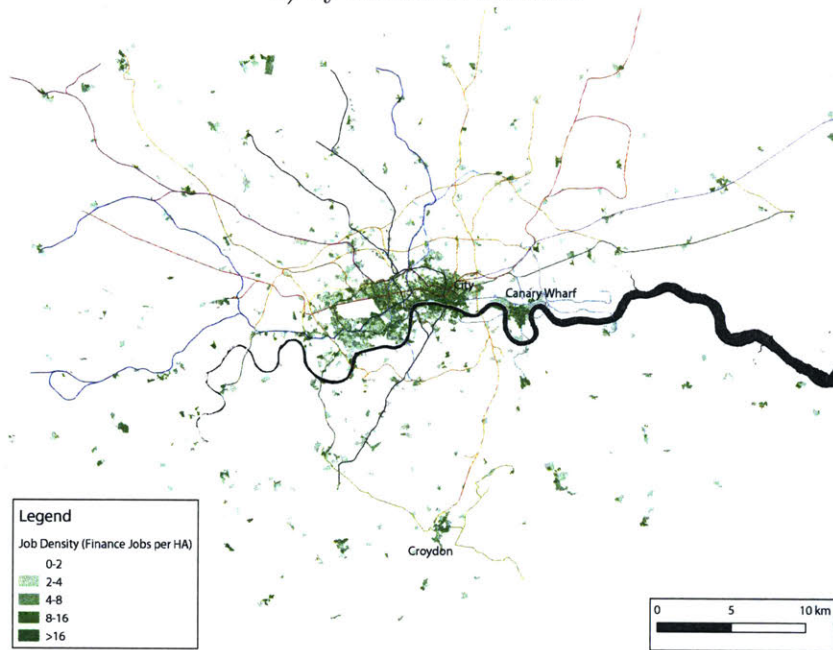
b) by work location

Figure 7.3: Density of finance industry workers (Data: ONS [Census 2011, QS605EW and WP605EW])

Legend

Residential Density (Healthcare workers per HA)

0-4
4-8
8-16
16-32
>32

a) by residence location

Legend

Job Density (Healthcare Jobs per HA)

0-2
2-4
4-8
8-16
>16

b) by work location

Figure 7.4: Density of healthcare industry workers (Data: ONS [Census 2011, QS605EW and WP605EW])
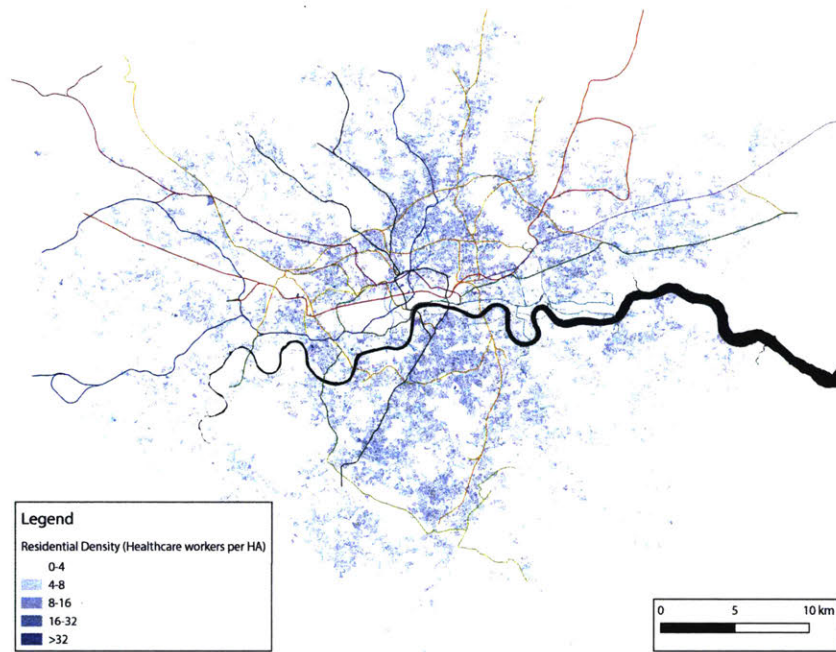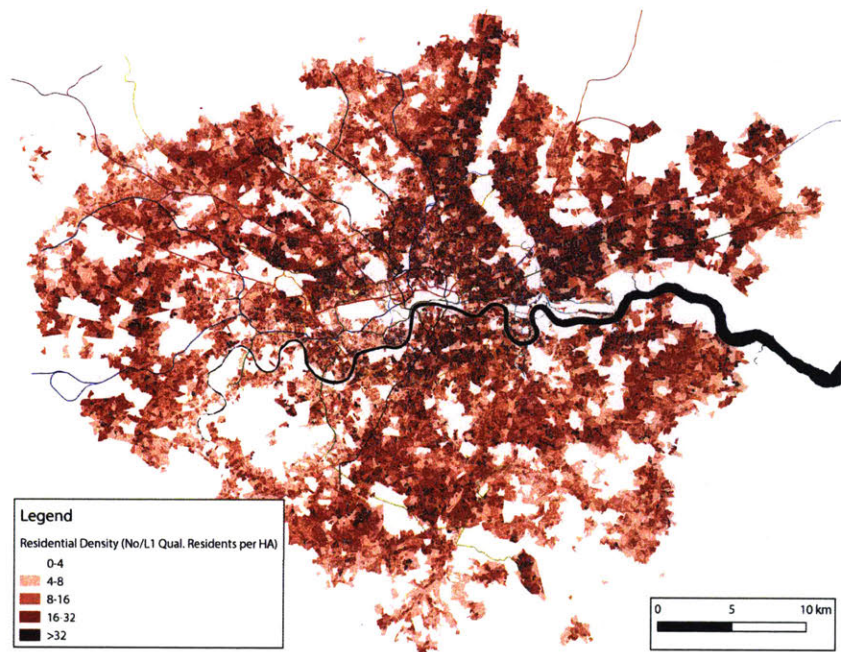
a) by residence location
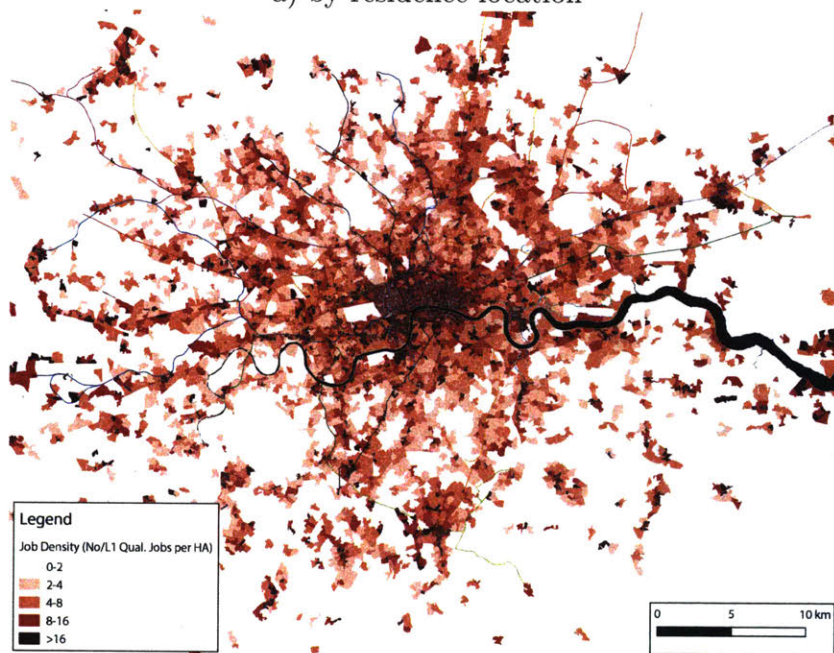
b) by work location

Figure 7.5: Density of residents with no or Level 1 Qualification (Data: ONS [Census 2011, QS501EW and WP501EW])

Table 7.1 includes the total values for the worker/residential categories mapped above. Note that the total number of jobs exceeds the total number of workers by approximately 1 million, and a similar pattern holds for the finance and healthcare industries, as many people who work in Greater London live outside it. There are approximately twice as many low-qualification working-age residents (1.8 million) as low-qualification jobs (923 thousand). In contrast, the number of college-educated residents (2.5 million) barely exceeds the Level 4 Qualification jobs (2.4 million), indicating a much tighter labor market.

Table 7.1: Resident and Worker Totals (thousands), London

	Total	Finance	Healthcare	No/L1 Qual.	L4 Qual.
Residents (16-74 yo)	6,117	–	–	1,855	2,470
Workers	3,999	306	429	–	–
Jobs	5,035	431	514	923	2,401

For visualization purposes, worker industries were compiled into ten classes[1], then disaggregated into a dot-density map, using building footprints as boundaries. The results are shown in Figures 7.6 - 7.8

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[1]Following http://fragile-success.rpa.org/maps/jobs.html, as shown in Figure 7.6
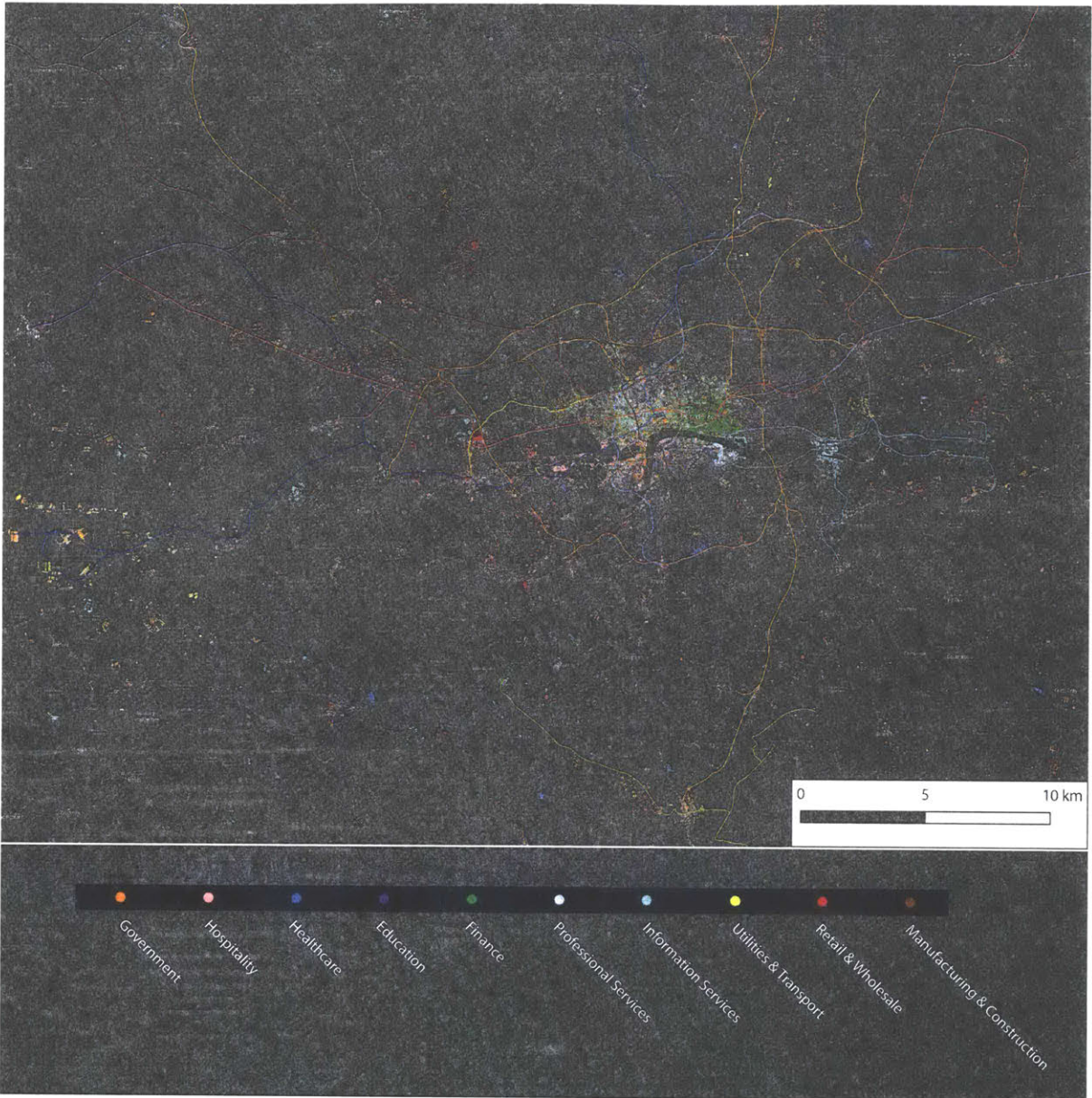
Figure 7.6: Locations of Greater London jobs (Data: ONS [2011 Census], OpenStreetMap contributors; Styling: Mapbox)

Figure 7.7: Jobs in Central London and Canary Wharf (Data: ONS [2011 Census], OpenStreetMap contributors; Styling: Mapbox)

Figure 7.8: Jobs in the City and West End (Data: ONS [2011 Census], OpenStreetMap contributors; Styling: Mapbox)

7.2.2 Transport network

The baseline transport network was built using timetables from the TfL Unified API for TfL services[2], a compiled GTFS feed for National Rail services[3], and OpenStreetMap data[4] for pedestrian routing. The resulting network includes 21,468 stops and stations.

For the results in Section 7.4, adjustments for reliability were made in a bus-only network by processing the Stop Events table[5] into a timetable of actual stop arrivals and departures for four weekdays (4-8 April, 2016). This network includes 20,329 stops. The low fare of buses relative to other modes make this an appropriate analysis, especially as the cost advantage of bus-only trips will increase with the extension free transfers, one of the Mayor's campaign promises. While an accessibility analysis that included travel by underground, national rail, automobile, and other modes, as well as constraints on cost, would be more informative, but archived real-time vehicle location data for these modes were not readily available.

7.3 Model - Unemployment Rates

The analysis below tests spatial error models to explain the output-area-level unemployment rate[6], with the form:

$$y = X\beta + \epsilon_s$$

$$\epsilon_s = \lambda W \epsilon + u$$

$$w_{ij} = \begin{cases} 1, \forall i \neq j, d < 500\text{meters} \\ 0, \text{otherwise} \end{cases}$$

(see Anselin (1988))

In this model, λ is a parameter representing the spatial autocorrelation of random error terms, and W is a matrix of distance-based weights. Values of λ approaching unity indicate the strong presence of spatial effects not explained by X. Basic spatial lag models were also tested; while there may be an argument for spatial lag effects, spatial error models were selected for discussion here based on Lagrange Multiplier diagnostics[7].

---

[2]https://api.tfl.gov.uk/, processed with https://github.com/CommuteStream/tflgtfs

[3]http://www.gbrail.info/

[4]https://mapzen.com/data/metro-extracts/metro/london_england/

[5]This table is prepared as an input to the ODX algorithm described in Gordon et al. (2013)

[6]The unemployment rate tested here and in the discussion that follows is a slightly modified version of the standard definition. It includes in the numerator both those actively looking for work in the four weeks before the Census day in 2011, as well as those who were not economically active but did not specify one of the listed reasons; this sum is divided by the total workforce in each block. For the area tested, the correlation between this value and the standard definition of unemployment is 0.91.

[7]see Anselin, 2005: http://csiss.org/clearinghouse/GeoDa/geodaworkbook.pdf

The independent variables tested include the following demographic variables, both of which are expected to correlate positively with unemployment:

Pct-LQ Percent of the output area's workforce that has low qualification

Pct-ME Percent of the output area's population that is of a minority ethnic group

The following variables related to accessibility are also tested:

a^{sch} The scheduled level of accessibility to all jobs (in millions), which is expected to correlate negatively with unemployment.

a^{sch}_{LQ} The scheduled level of accessibility to low-qualification jobs (in millions), which is also expected to correlate negatively with unemployment.

a^{sch}_{HQ} The scheduled level of accessibility to all other jobs (in millions), which may correlate positively with unemployment, if it captures confounding land-use effects, such as poorer residents residing in central areas for access to social services.

a^{mean}_{LQ} The mean actual level of accessibility to low-qualification jobs (in millions), which is expected to correlate negatively with unemployment.

PD_a The percent difference between scheduled and actual mean accessibility, which is expected to correlate positively with unemployment rate.

COV_a The coefficient of variation of actual accessibility, which is expected to correlate positively with unemployment rate.

7.4 Results - Reliability and Unemployment Rates

This section combines A and B adjustments, considering reliability-adjusted access by bus to employment in jobs with low educational requirements (i.e. held by workers whose highest level of qualification does not exceed Level 1). This analysis assumes a random departure between 8:00 and 8:30 and a limit of four transfers between buses, and it includes waiting times and walking times to and from bus stops.

As an example, in Figure 7.9, 60-minute isochrones from an origin in the London Borough of Haringey for actual bus service on four days, and for scheduled service, are superimposed to create a reliability surface. To most destinations, travel by bus was faster than scheduled on at least one of the four days analyzed (the area around Euston being a notable exception). For many destinations south of the origin, especially between Euston, Shoreditch, and Bethnal Green, the grey gradient inside the scheduled isochrone indicates that actual reach on the worst day fell short of the reach based on scheduled service.

Legend

⭐ Haringey

☐ 60-min Isochrone (sch)

Reliability of 60-min reachability

☐ 0/0 days
▨ 1/4 days
▨ 2/4 days
▨ 3/4 days
▨ 4/4 days
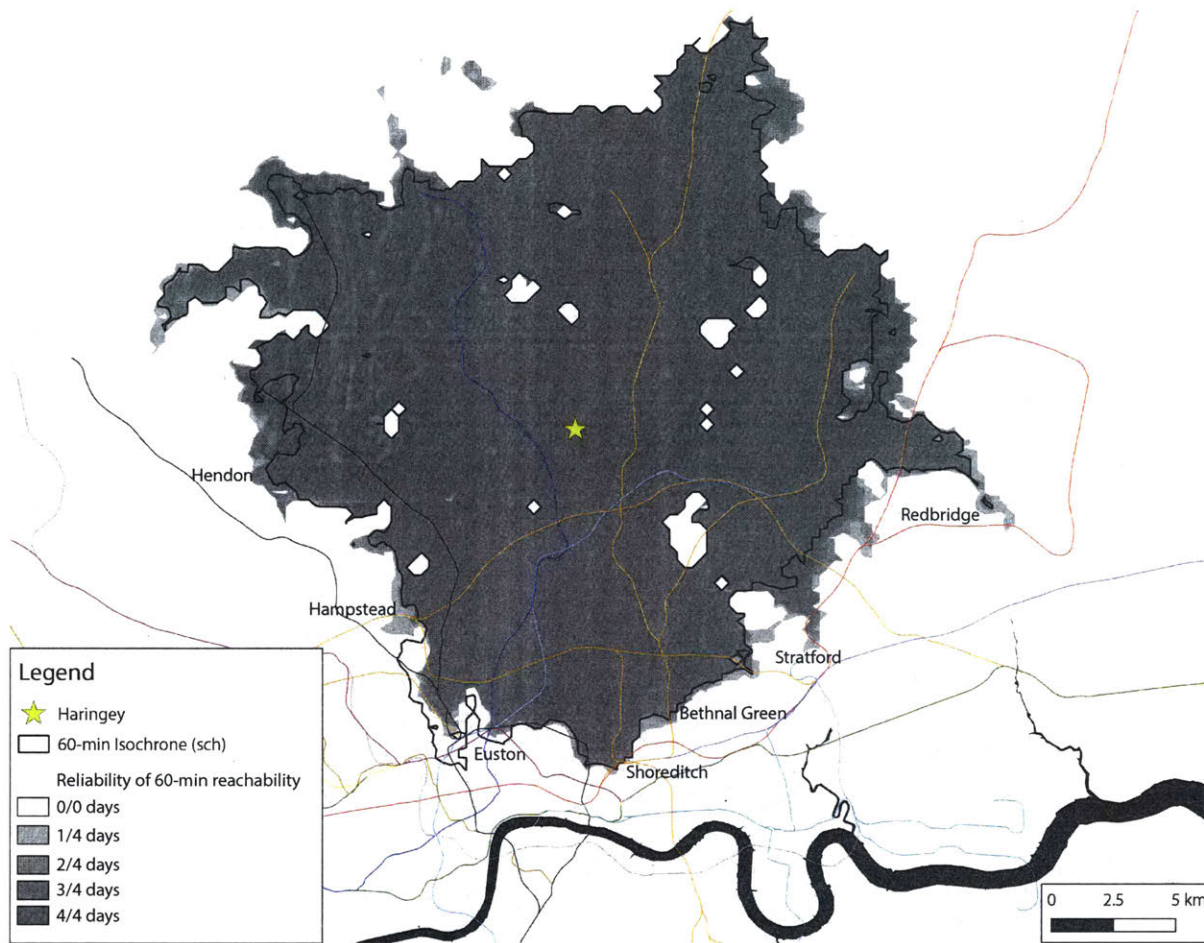
Figure 7.9: 60-minute isochrones, departing from Haringey between 8:00 and 8:30 AM on four weekdays in April 2016.

For every destination zone j, the values of $t^k_{\text{Haringey}-j}$ can be multiplied by the value of $q_j(D)$, then binned to form cumulative plots of $a^k_{\text{Haringey}}(D, \tau)$. Such cumulative plots for $D =$ low-qualification jobs and $D =$ Level 4 Qualification jobs are included below as Figures 7.10 and 7.11, respectively. Note that the y-axis scale for the accessibility to Level 4 Qualification jobs is four times the scale for accessibility to low-qualification jobs. The slope of the low-qualification curves is fairly gradual, given the relatively dispersed locations of low-qualification jobs; in contrast, the high-qualification curves increase markedly as travelers are able to reach central London, which happens within approximately 40 minutes using all public transport modes, and approximately 70 minutes when using only buses. Congestion in central London likely explains much of the spread between the curves – both schedule nonconformity and service variability.

For the four weekdays considered, PD_a and COV_a (as defined in subsection 7.1.1) for access to low-qualification jobs were calculated for each of the 24,920 Census 2011 output areas in
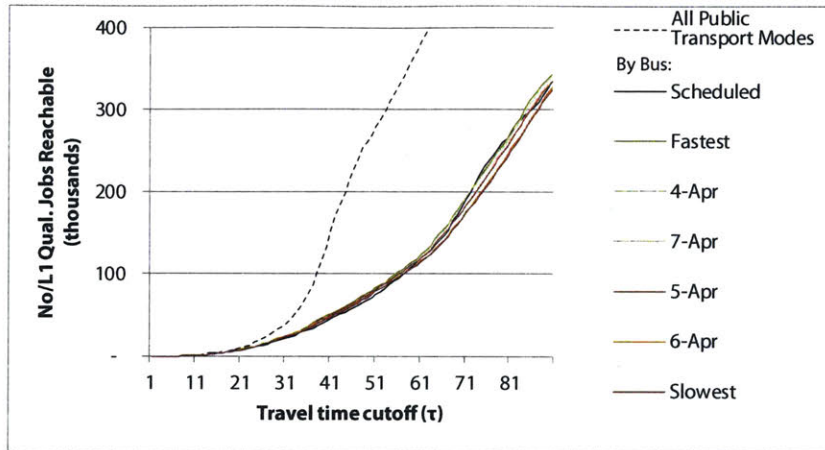
Figure 7.10: Number of No/L1 Qualification jobs reachable from Haringey, by travel time cutoff
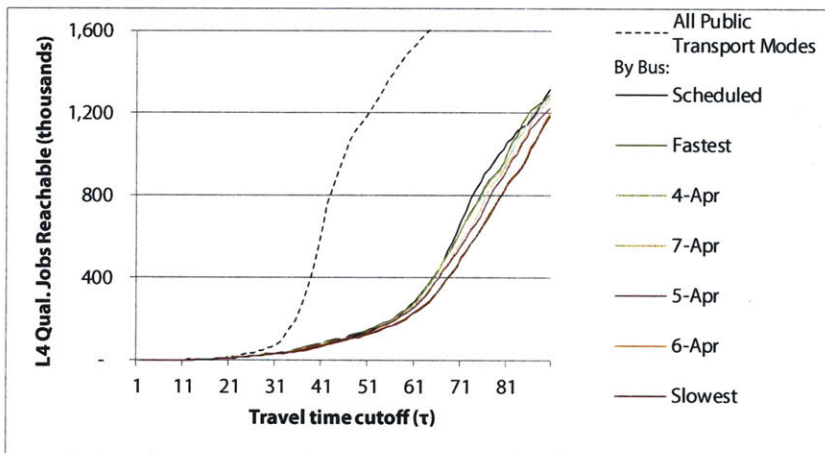
Figure 7.11: Number of L4 Qualification jobs reachable from Haringey, by travel time cutoff

Greater London. A simple negative linear impedance function with a cutoff τ of 90 minutes[8] and five-minute bins (for computational reasons) were used to calculate the values of a_i, which can be interpreted as the number of jobs easily reachable from output area i. With this formulation, 20 thousand jobs located 45 minutes from i are considered equivalent to only 10 thousand jobs located at i. The values of PD_a and COV_a for each output area are shown in Figures 7.12 and 7.13.

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[8] $f(t) = 1 - t/90$, see subsection 2.5.3
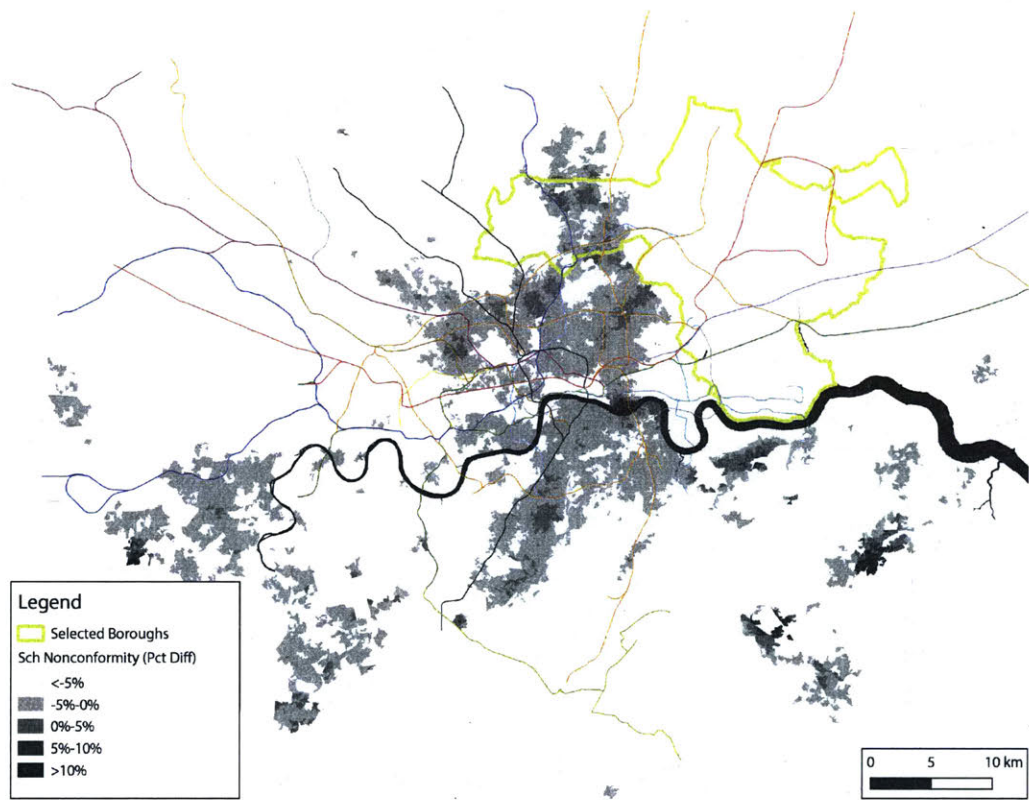
Figure 7.12: Percent difference between scheduled and actual accessibility (mean over four days) by bus to low qualification jobs in London
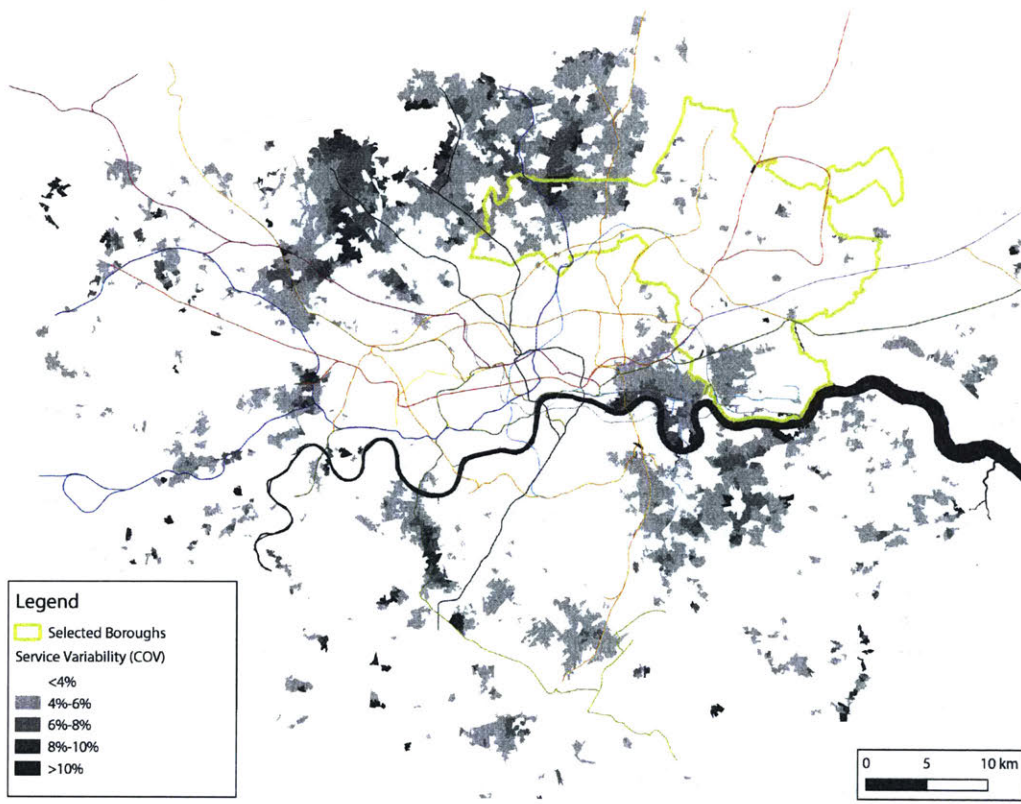
Figure 7.13: Coefficient of variation of actual accessibility (over four days) by bus to low qualification jobs in London

The 2,917 output areas with at least five residents per hectare in the Boroughs of Haringey, Waltham Forest, Newham, and Redbridge (outlined in Figures 7.12 and 7.13) were used to test models of the form described above. These contiguous boroughs have relatively high bus mode share and a wide range of accessibility levels and unemployment rates, including some of the most prominent clusters of unemployment in the region (see Figure 7.2).

Table 7.2 shows the estimation results for various model specifications. The two demographic variables included in Model 1 were found to be highly significant ($p < .001$) across the models, with the expected positive signs. The large coefficient and significance of λ suggest, unsurprisingly, that the unemployment rates of nearby output areas tend to be strongly correlated in ways that are not fully explained by the explanatory variables.

Model 2 adds a^{sch} as an explanatory variable, and it has a positive estimated coefficient; this may arise from the tendency of clusters of unemployment to be located relatively centrally, where accessibility to total jobs is high.

Model 3 decomposes scheduled accessibility into low and high qualification jobs, and the estimated signs have opposite coefficients. This supports the interpretation that areas of high unemployment tend to be centrally located, and that better accessibility to low-qualification jobs is correlated with lower unemployment. Caution is warranted with this model, as the job accessibility variables included are highly correlated.

Model 4 includes the measures of unreliability discussed above; schedule nonconformity (at least as measured based on the limited sample of the four days analyzed) is not significant ($p = .224$), while service variability (COV_a) is ($p < .001$). The positive sign of COV_a matches expectations.

In Model 5, the mean level of actual accessibility to low-qualification jobs is used instead of the scheduled level and a nonconformity level. This improves the significance of the estimates as well as the model fit (the Schwarz criterion drops from -12629 in Model 1 to -12690 in Model 4 and -12696 in Model 5). Note the similar magnitudes of a_{LQ}^{mean} and COV_a. While causality is not clear and any extrapolation beyond this limited sample would be suspect, these coefficients suggest an increase of 1 million low-qualification jobs easily reachable by bus during the morning of an average day would be correlated with an approximately equal reduction in unemployment as a decrease of 1% in the network-level variability of bus service during that time window.

Table 7.2: MLE Results for Spatial Autoregressive Models (n = 2917 output areas)

	Model 1 - Demographics			Model 2 - All Jobs			Model 3 - Segmented			Model 4 - Unreliability			Model 5 - Actual		
	Coef.	SE	p-val	Coef.	SE	p-val	Coef.	SE	p-val	Coef.	SE	p-val	Coef.	SE	p-val
Const.	0.005	0.003	.104	-0.017	0.004	.000 **	0.002	0.007	.768	-0.003	0.008	.700	-0.011	0.006	.078 .
$Pct\text{-}LQ$	0.144	0.007	.000 **	0.153	0.007	.000 **	0.152	0.007	.000 **	0.151	0.007	.000 **	0.151	0.007	.000 **
$Pct\text{-}ME$	0.095	0.005	.000 **	0.093	0.004	.000 **	0.100	0.005	.000 **	0.096	0.004	.000 **	0.095	0.004	.000 **
a^{sch}				0.049	0.005	.000 **									
a^{sch}_{QH}							0.147	0.028	.000 **	0.099	0.028	.000 **	0.080	0.017	.000 **
a^{sch}_{QL}							-0.673	0.203	.001 **	-0.414	0.196	.035 *			
a^{mean}_{QL}													-0.233	0.126	.065 .
PD_a										0.022	0.018	.224			
COV_a										0.229	0.050	.000 **	0.238	0.049	.000 **
λ	0.669	0.027	.000 **	0.537	0.033	.000 **	0.534	0.033	.000 **	0.478	0.036	.000 **	0.479	0.036	.000 **
Pseudo-R^2	0.526			0.528			0.530			0.530			0.530		
AIC	-12647			-12705			-12716			-12732			-12732		
SIC	-12629			-12681			-12686			-12690			-12696		
Breusch-Pag.	159	5 DF		162	3 DF		155	4 DF		157	6 DF		159	5 DF	

7.5 Results - Connectivity advantage by employment class

To test the hypothesis about connectivity advantage, two different example segmentations were chosen. First, finance and healthcare were selected as example industries. For example qualification levels, the extremes of those with no or Level 1 qualifications, and those with at least Level 4 qualifications, were selected. This approach seeks new ways to quantify what has long been recognized:

> Certain categories of residents, by reason of their household or personal characteristics, find themselves seriously deprived with respect to accessibility... They may suffer from combinations of these disadvantages such that the various deprivations become negatively reinforcing. (Foley, 1974, p. 205)

Table 7.3 shows how many workers are reachable within 45 minutes for the average (job-weighted) firm in each of these classes. For example, the average job in London can be reached within 45 minutes by 780 thousand workers, 74 thousand finance workers, and 77 thousand healthcare workers. The average finance job can be reached in 45 minutes by 1.2 million workers, 119 thousand of whom are finance workers. Even though there are more healthcare workers than finance workers in London (see Table 7.1), the average healthcare job can be reached in 45 minutes by only 64 thousand healthcare workers.

Table 7.4 highlights this disparity by normalizing by the total number of workers in each class. Within 45 minutes, the average finance job is reachable by 39% of the region's finance workforce, while the corresponding figure for healthcare jobs is only 15%. A similar disparity exists between the extremes of the qualification dimension.

Instead of a binary cutoff with $\tau = 45$ minutes, Table 7.5 uses a modified negative linear functional form[9] (again, for computational convenience) to convey the number of effective or "easily reachable" workers. The results follow the same pattern as the preceding tables, with slightly higher values. A_{Adv} is shown for the industries and qualification levels. In line with the second set of hypotheses guiding this chapter, jobs in finance and held by workers with at least Level 4 Qualifications have $A_{\text{Adv}} > 0$, while jobs in healthcare and held by residents without qualifications above Level 1 have $A_{\text{Adv}} < 0$.

Tables 7.6 and 7.7 show these results from the perspective of residents and workers. Again, finance workers and residents with at least Level 4 Qualifications have $A_{\text{Adv}} > 0$, while healthcare workers and residents without qualifications above Level 1 have $A_{\text{Adv}} < 0$.

---

[9]

$$f(t) = \begin{cases} 1 & , t \leq 30 \\ \frac{2}{3} & , 30 < t \leq 45 \\ \frac{1}{3} & , 45 < t \leq 60 \\ 0 & , t > 60 \end{cases}$$

Table 7.3: Workforce Connectivity (within 45 minutes)

| | Thousands of Workers Reachable | | | | |
	All	Finance	Healthcare	No/L1 Qual.	L4 Qual.
Job (unmatched)	780	74	77	306	552
Finance Job	1,243	119	-	-	-
Healthcare Job	636	-	64	-	-
No/L1 Qual. Job	591	-	-	240	-
L4 Qual. Job	917	-	-	-	656

Table 7.4: Normalized Workforce Connectivity (within 45 minutes)

| | Percent of Workers Reachable | | | | |
	All	Finance	Healthcare	No/L1 Qual.	L4 Qual.
Job (unmatched)	19%	24%	18%	16%	22%
Finance Job	31%	39%	-	-	-
Healthcare Job	16%	-	15%	-	-
No/L1 Qual. Job	15%	-	-	13%	-
L4 Qual. Job	23%	-	-	-	27%

Plots of the distribution of job accessibility across workers and residents are shown in Figures 7.14 and 7.15. A very small proportion of healthcare workers has access to over 200 thousand healthcare jobs, while a substantial portion of finance workers have access to over 200 thousand finance jobs. Though there are 923 thousand jobs held by low-qualification workers in the region, essentially no low-qualification residents can reach more than 500 thousand of them. This constrained accessibility is masked if matching is ignored (see the "All" line in Figure 7.15); a relatively small proportion of all residents have access to fewer than 500 thousand total jobs.

Table 7.5: Workforce Connectivity (effective)

	All	Finance	Healthcare	No/L1 Qual.	L4 Qual.
			Thousands of Workers Reachable		
Job (unmatched)	888	79	90	363	610
Finance Job	1,342	121	-	-	-
Healthcare Job	754	-	77	-	-
No/L1 Qual. Job	695	-	-	289	-
L4 Qual. Job	1,028	-	-	-	710
Connectivity Advantage		64%	-1%	-6%	28%

Table 7.6: Job Connectivity (effective)

	All	Finance	Healthcare	No/L1 Qual.	L4 Qual.
			Thousands of Jobs Reachable		
Worker (unmatched)	1,128	145	98	161	624
Finance Worker	1,310	170	-	-	-
Healthcare Worker	1,072	-	93	-	-
No/L1 Qual. Res.	992	-	-	144	-
L4 Qual. Res.	1,253	-	-	-	697
Connectivity Advantage		18%	-5%	-10%	12%

Table 7.7: Normalized Job Connectivity (effective)

	All	Finance	Healthcare	No/L1 Qual.	L4 Qual.
			Percent of Jobs Reachable		
Worker	22%	34%	19%	17%	26%
Finance Worker	26%	39%			
Healthcare Worker	21%	-	18%		
No/L1 Qual. Resident	20%	-	-	16%	
L4 Qual. Resident	25%	-			29%
Connectivity Advantage		18%	-5%	-10%	12%

Distribution of Job Accessibility

Matched by Industry
— Finance
— Healthcare
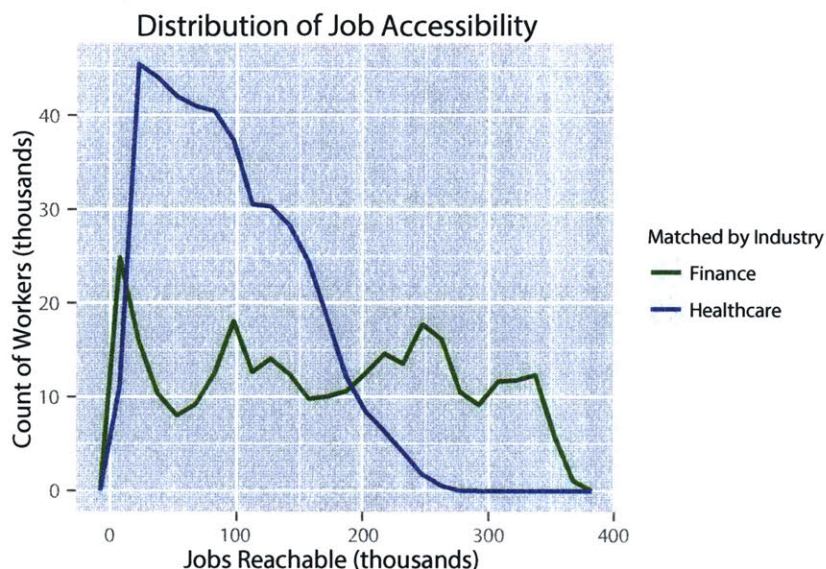
Figure 7.14: Distribution of accessibility of workers to jobs, selected industries in London

These patterns come across more clearly in the cumulative diagrams shown in Figures 7.16 and 7.17[10]. The dashed lines in these figures represent all workers/residents (corresponding to the first row of Table 7.6), while the solid lines represent matched workers/residents.

Figure 7.16 suggests that the median worker is within easy reach of approximately 93 thousand (or 18% of the region's total) healthcare jobs. The median healthcare worker has slightly lower levels of access. In contrast, the connectivity advantage of finance workers is clear; they have higher levels of access to finance jobs than the population of workers as a whole.

Figure 7.17 shows jobs within easy reach for workers with different levels of qualifications. High-qualification jobs tend to be located in accessible locations, so they are more easily accessed by workers generally. The locational patterns of high-qualification residents reinforce this advantage (i.e. the pink line is above the corresponding black dashed lines). In contrast, low-qualification workers see a connectivity disadvantage. Figure 7.17b) shows the absolute number of jobs reachable for the lowest decile of the same classes of residents. The worker at the 2.5th percentile of access to all jobs is within easy reach of about 115 thousand jobs; the worker at the 2.5th percentile of access to high-qualification jobs is within easy reach of about 40 thousand such jobs; and the worker at the 2.5th percentile of access to low-qualification jobs is within easy reach of about 28 thousand such jobs. Furthermore, low-qualification workers tend to have access to fewer jobs than do workers in general.

---

[10]Note that these are similar to Figure 6.1, which is copied from Grengs (2012). Also note that the axes have been rotated from the frequency distribution plots above, which had number of jobs reachable on the x-axis.
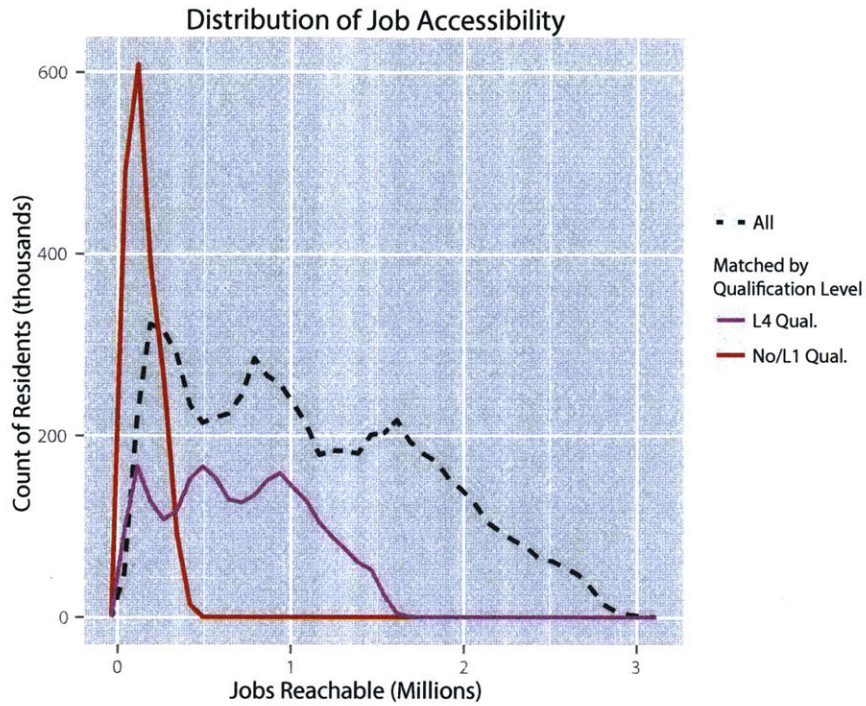
Figure 7.15: Distribution of accessibility of residents to jobs, selected qualification levels in London

Martens (2017) argues that accessibility should be improved for those who experience the least. Considering that available positions are likely to be only a small fraction of jobs reachable, the connectivity disadvantages shown in this analysis might point to substantial access barriers to low-qualification job seekers.

Job Connectivity by Population Percentile
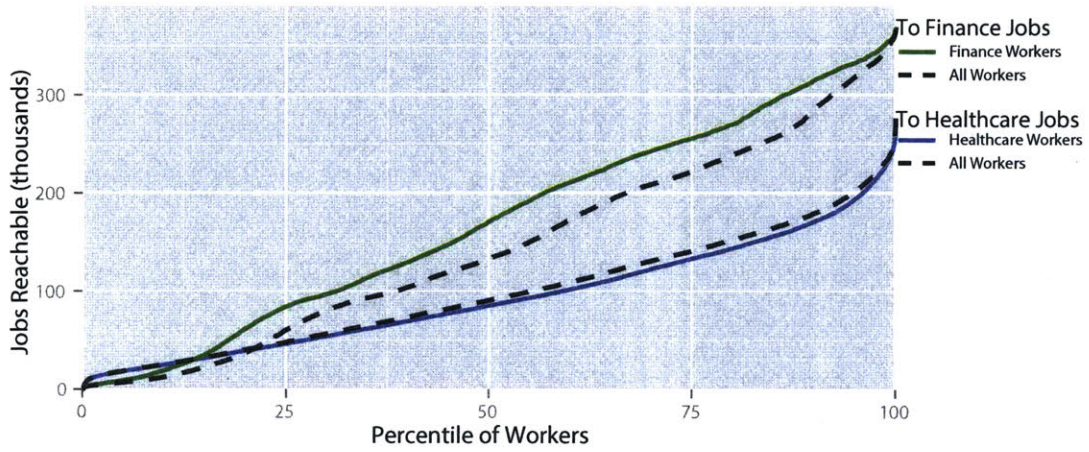
a) Absolute number of jobs

Job Connectivity by Population Percentile
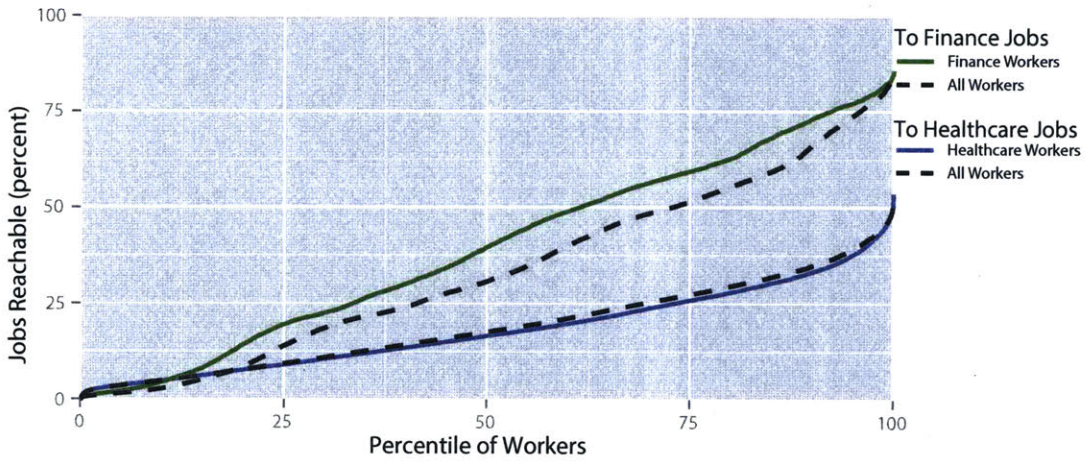
b) Percent of jobs in industry

Figure 7.16: Cumulative distribution of accessibility of workers to jobs, selected industries

Job Connectivity by Population Percentile

a) Full distribution

Job Connectivity by Population Percentile

b) Lowest decile

Figure 7.17: Cumulative distribution of accessibility of residents to jobs, selected qualification levels

7.6 Discussion

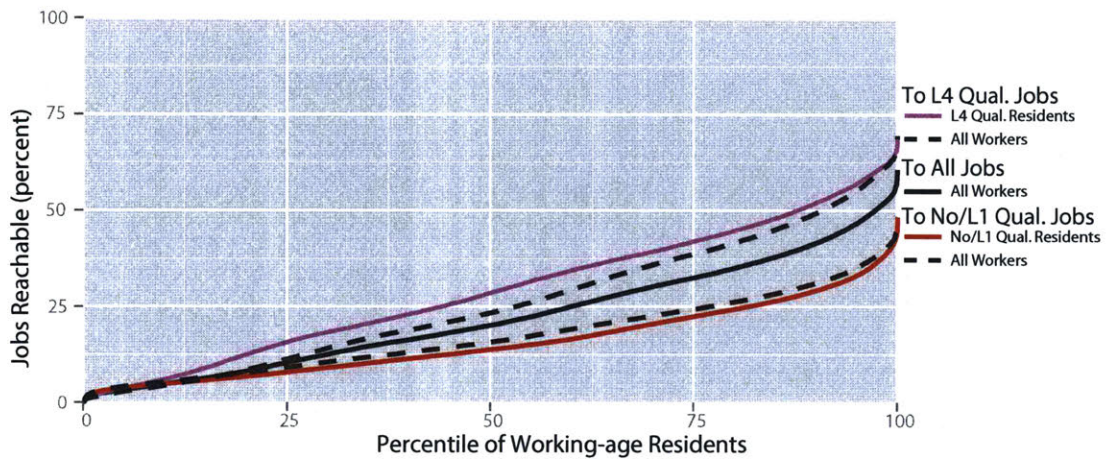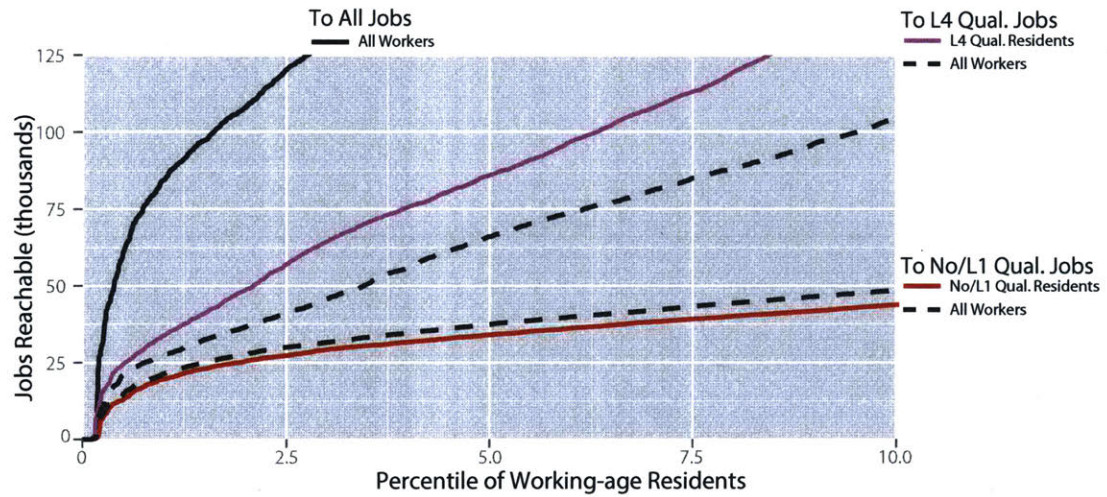The findings of this analysis echo the caution of Manaugh and El-Geneidy (2012), that "focusing on all jobs could easily misrepresent which jobs are truly accessible and which are not, based on skills, knowledge and experience." If accessibility analyses of transport investments do not account for such matching constraints (class B), they may underestimate benefits provided to advantaged groups, and overestimate the benefits provided to disadvantaged groups, a pernicious bias. Furthermore, adjustments of class A suggest that unreliability, as measured by the variation in accessibility, correlates positively with unemployment. Given concerns about endogeneity, confounding land-use factors, and unexplained spatial autocorrelation, these findings cannot be taken as definitive. More refined multi-level models, incorporating individual attributes, instrumental variables, and spatial regimes (e.g. at the Borough level) could address some of these shortcomings. Nonetheless, this analysis suggests constrained accessibility metrics can be relevant to broader policy goals.

An extension of this analysis could consider how these accessibility findings align with reported trip length distributions for workers in different employment classes. A comparison of connectivity advantage across an exhaustive set of industries, beyond the examples considered here, might also be informative. If certain industries exhibited high connectivity advantages, but not high elasticities of productivity with respect to effective density, there might be evidence for including thick market effects as additional to effective density wider economic benefits in project appraisal.

Other constraints have been ignored in this analysis, but they may play an important role, especially in near-capacity operations. Consider the back-of-the-envelope example shown in Figure 7.18. The combined reach of the Jubilee Line Extension and Docklands Light Rail enables nearly 100 thousand potential employees to be within reach, but the capacity they provide (ignoring other constraints in the transport network) may be closer to 80 thousand arriving passengers per hour (as suggested by the lower dashed line). The Elizabeth Line will expand transport's reach (represented by the purple fringe) as well as its capacity (represented by the upper dashed line). In an expansive and heavily used public transport network, the capacity added by new links is likely to be of greater value than the incremental gain in reach. To capture these effects at a network level (class D), more advanced modeling (or perhaps the incorporation of retrospective real-time passenger location data, such as that becoming available from Wi-Fi device tracking) would be needed.
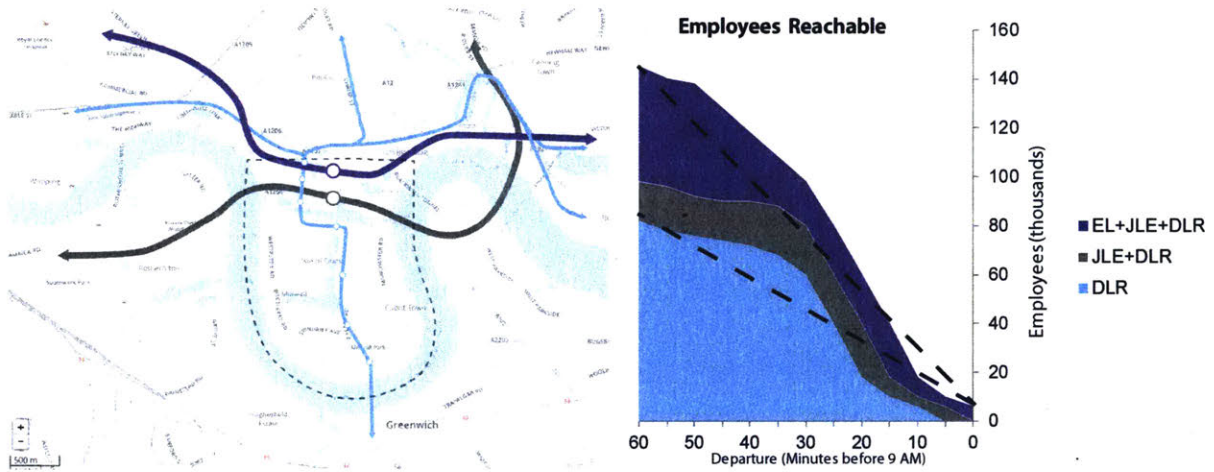
Figure 7.18: Illustrative example of transit accessibility and cordon capacities at Canary Wharf

Chapter 8

Constrained Healthcare Access

Frankly, transportation agencies know surprisingly little about the people and places they serve... where people live, where people work, where they get their healthcare. Most transportation agencies don't know that. And honestly some people – and I'm not just talking about the folks who work for me – have startlingly little interest in that piece of information, or startlingly little access to that piece of information.

– Stephanie Pollack, Massachusetts Secretary of Transportation
at a Brookings Institution discussion on accessibility metrics in January, 2017

Transportation affects residents' health, not only through negative externalities such as pollution, but also by enabling people to reach healthcare providers (or not). The environmental justice paradigm recognizes these overlapping impacts, and the unevenness of amenities like reliable transportation (Bullard et al., 2004). Federal environmental justice policy in the US requires transit agencies to assess whether service changes may have disparate impacts or disproportionate burdens on vulnerable communities. Such analyses typically focus on measures of realized mobility, such as disparities in travel time calculated using surveys or automatically collected data (e.g. Williams et al. (2014), Dumas (2015)). Such methods may not be sufficient to account for trips that people make infrequently, and for which information is much less readily available, such as healthcare. Compounding these data difficulties are institutional fragmentation and misaligned objectives, at least in the US, as exemplified by the myriad non-emergency transportation (NEMT) programs under Medicaid:

> Both public transit and Medicaid NEMT have a similar goal – they want to provide individuals, especially those without other options, access to health care. And there's an expectation that it will improve outcomes. Beyond that, they don't have many additional goals or objectives in common, and in fact they sometimes diverge (NASEM, 2016, p. 126).

Transport barriers to healthcare access, such as high fares and unreliable service, can impose

substantial costs on society. These barriers are often highest for lower-income populations with pressing health needs. One health center in Worcester, Massachusetts, estimates that each missed appointment imposes an average of $154 in staff and rescheduling costs; furthermore, 51% of its patients miss an appointment due to a transportation problem in a given year, resulting in an annual cost of $740,000 due to transportation problems (NASEM, 2016). Patients may also face rescheduling difficulties and the costs of more severe health needs due to delayed care. In short, if a transportation agency provides unreliable access to healthcare facilities and causes patients to arrive late to or miss their appointments, it may be externalizing costs to those patients and the broader healthcare system.

Neutens (2015) reviews accessibility and health care research through the lens of transport geography, noting that gravity measures and extensions of the two-step floating catchment area (2SFCA) method are widely used. The latter is an example of an adjusted-accessibility measure (of class C discussed in subsection 6.3.3 of this dissertation). While accessibility measures have a long history in healthcare facility location decisions, travel times are generally taken as a static input, with little attention paid to actual transportation supply or matching constraints. In other words, adjustments of class A (to account for varying transport supply) and B (to account for the fact that patients may have particular matching criteria beyond travel distances/times that dictate their choice of destinations) are often ignored.

The goals of this chapter respond in part to the research needs identified by Neutens (2015, p. 14), "for more spatially disaggregated, individualized and temporally aware accessibility metrics", without delving into detailed space-time accessibility measures. Such measures are often more appropriate for planning facility locations and operating hours, and they require detailed data on fixed constraints in people's time-space trajectories. Instead, this chapter uses data from a survey of community health center patients, which was conducted by others to gauge transportation's role as a social determinant of health. This chapter's analysis relies on more disaggregate geographies (primarily at the Census block level), building a sample of synthetic patients from a basic and relatively imprecise survey of patients conducted in community health center waiting rooms in Boston. Using this survey implicitly incorporates individual matching constraints, as the sampling design relies on a revealed preference for a given health center.

By incorporating actual MBTA transit service over the course of ten weekdays, this accessibility analysis seeks to be more "temporally-aware," and to delimit the role transit reliability can play in the many overlapping factors determining healthcare access. Much of the MBTA's equity analysis is conducted at the route, rather than network level. This chapter focuses on network-level measures of reliability, recognizing that lower-income communities of color are likely to face compounded barriers (e.g. through multiple transfers) that route-level analysis may underestimate. Finally, while the primary focus of the chapter is on operational reliability of the transit network, the importance of equity considerations is also recognized through attention to issues of gentrification and displacement.

8.1 Problem formulation and hypotheses

The hypotheses below concern the accessibility of the health centers, by walking and transit, for residents departing between 7 and 9 AM. With health care centers spread throughout the metropolitan area, and the general (as opposed to specialized or emergency) care they provide, patients would be expected to have fairly short trips. This analysis assumes patients travel to their appointments directly from their home locations, ignoring trip-chaining that could be incorporated by more robust activity-based modeling (e.g. the approach of Dong et al. (2006)). The assumption of a departure time window of 7 to 9 AM may also be quite strong, but respondents' departure/arrival times were not recorded in the survey, so this is difficult to gauge.

Given that origins are fixed by these assumptions, levels of accessibility are solely a function of the transit network's performance. Levels of accessibility based on actual operations can accordingly represent the reliability of transit service at a network level. Users may experience unreliability in terms of nonconformity with published schedules, and in terms of day-to-day service variability, and these can both be represented in terms of travel time and accessibility. It is generally expected that measures of unreliability will correlate positively with self-reported late arrivals/missed appointments in the survey.

Because the synthetic patient population generated (as described below) is intended to represent respondents who actually traveled to the health center by transit, measures of realized mobility (not just the potential for interactions) are appropriate. The time the average transit-using patient spends traveling to health center i can be calculated from a cumulative opportunity plot as $\bar{t}_i = \tau_{\max} - \int_0^{\tau_{\max}} a_i'(\tau)d\tau$, where $a_i'(\tau)$ is the percent of health center i's patients reachable in less than τ minutes and $\tau_{\max}$ is at least the longest observed trip duration. Transit's schedule nonconformity for a healthcare center i can be calculated as the (percent) difference between a representative value of $\bar{t}_i$ (e.g. the mean over a set of days) and $\bar{t}_i^{\mathrm{sch}}$. Such indicators are readily interpreted (e.g. it takes the average patient 5 minutes [or 10%] longer to arrive than would be expected based on scheduled service). Service variability over a set of days k can be represented as the standard deviation or coefficient of variation of $\bar{t}^k$.

Indicators of accessibility to all residents can also be calculated for each health center. A basic cumulative opportunity measure requires selecting a value for τ. Alternatively, the number of residents in each block j can be discounted by $f_i(t_{ij})$, where f_i is the frequency distribution of reported travel times by transit to the health center. This method of calculating "effective" residents is analogous to using empirical trip-length distributions to calibrate impedance functions in the trip-distribution step of the traditional four-step travel demand model. It avoids the requirement to select a value of τ by collapsing the cumulative opportunity accessibility plot into a single number, a_{eff}. Schedule nonconformity using this accessibility definition can be calculated as the (percent) difference between $a_{\mathrm{eff}}^{\mathrm{sch}}$ and a representative value of a_{eff} (e.g. the mean over a set of days). Note that the order here is reversed from the travel time measure. This is so that in both cases, larger positive values represent increasing

nonconformity with scheduled service. And as above, service variability over a set of days k can be represented as the standard deviation or coefficient of variation of a_{eff}^k, with larger values representing more variability in service.

8.1.1 Health center-ZIP code pairs

It is expected that at the level of health center-ZIP code pairs, the percent of respondents reporting a late arrival/missed appointment due to unreliable transit in the past year (LA/MA) will correlate positively with the time-based measures of 1) schedule nonconformity and 2) service variability discussed above. These are intuitive hypotheses; evidence supporting them may be less valuable as empirical findings *per se* than as corroboration of the approach taken to generating the synthetic patient residential locations and using them to calculate average travel times.

8.1.2 Health center averages

Aggregated to the health center level, it is also expected that LA/MA will correlate positively with schedule non-conformity and service variability, using both measures of travel time for synthetic patients and accessibility to effective residents.

8.2 Data

8.2.1 Survey of community health center patients

The Boston Alliance for Community Health (BACH), in cooperation with local transportation advocacy organizations, conducted a survey of patients during routine visits to community health centers in the summer and fall of 2015. Suitably complete responses for the analysis in this chapter were collected for 812 patients at 9 of the health centers (see Figure 8.1)[1].

Relevant questions on the survey include:

- Have you missed or been late to a health appointment in the past year because of public transit?

- If yes, why?

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[1]The number of respondents per health center ranged from 55 to 104.

- How do you normally get to the health center?

- How long does your trip to the health center take you?

- Home ZIP code

- Race/Ethnicity

Thirty-nine percent of all respondents replied yes to the first question about missing or being late to an appointment in the past year. The survey team classified responses to the second question using the categories of weather, cost of fares, missed transfer, scheduled maintenance, bus out of service/overcrowded, vehicle breakdown, handicap accessibility, and other. For this analysis, participants were coded as having a late arrival/missed appointment due to unreliable transit (LA/MA) if they responded yes to the first question, but not if they responded to the second question with reasons related only to weather, fare payment, or handicap accessibility. This filtering was done to remove responses reflecting service shutdowns in response to the record snowfall that affected Boston in early 2015, and other issues like affordability that are not directly related to the operational reliability of service.

Questions about home locations and travel times were collected with relatively low precision. Travel time to the health center was coded in 15-minute bins. Home locations were reported at the ZIP-code level only. Efforts to obtain more precise data on the travel patterns of health center patients were unsuccessful, in part due to HIPAA[2] privacy restrictions on individually identifiable health information.

8.2.2   Home locations

The distribution of, and access to, transit nodes within a ZIP code vary widely, making the ZIP-code level too aggregate for a meaningful analysis of transit travel times or accessibility. To address this issue, a set of synthetic patients was created by sampling from a population layer, consisting of one point representing the home location of each adult resident categorized by race/ethnicity. This population layer was created using the 2010 Census data at the block-level, for 71,544 blocks in Greater Boston [3]. For each respondent in the survey, ten points in the population layer were selected randomly from those within the respondent's home ZIP code and matching the respondent's race. Each health center is thus associated with ten times as many synthetic patients as respondents (i.e. ranging from 550 to 1040).

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[2]The US Health Insurance Portability and Accountability Act of 1996

[3]Census Table P12, counts of different race/ethnicity groups at the block level, was the primary data source for this layer. A cross-tabulation of race by earnings at the block level was also created, but was not used for the analysis in this chapter. The cross-tabulation was estimated using iterative proportional fitting at the block-group level, using ACS Table B2005 (race by earnings, for residents at least 16 years old) as the seed, ACS Table B20001 (earnings, for the population at least 16 years old with earnings) for the row totals, and aggregated counts of population by race from Table P12 as the column totals. The distribution of race by earnings for each block group was then assumed to be uniform across its constituent blocks. For visualization purposes, e.g. Figure 2.7, the points for each block were randomly distributed within building footprints of that block.

8.2.3 Transport network

To represent actual service, automatic vehicle location data for October 2016 were formatted into files loosely following the General Transit Feed Specification (GTFS). Scheduled service was derived from the MBTA's published GTFS feed for Fall 2016. Both of these feeds were transformed into digital networks suitable for routing calculations using the R5 algorithm (see subsection 2.5.6 and Conway et al. (2017)). The ten consecutive weekdays starting on Monday, October 17 were selected for analysis. For each of these days of actual operations and for the typical weekday schedule, the average travel time, assuming a random departure between 7 and 9 AM, from each health center to each of the 71,544 blocks in the region, was calculated. As in Chapter 7, these travel times include stop access/egress walking time along the OpenStreetMap pedestrian network, waiting time, and in-vehicle time. It is assumed that travel times between two given points are symmetric regardless of direction of travel (i.e. $t_{ij} = t_{ji}$). This simplifying assumption may skew results, but the distortion should be relatively small given the local travel considered and the lack of relevant directionally biased services.

The "actual" service feed includes trips and stop events (i.e. the arrival and departure of a vehicle at a stop) for:

- light rail service (the MBTA Green Line, see Fabian (2017));

- subway service (the MBTA's Red, Orange, and Blue Lines) from track-circuit train-location data;

- and MBTA-operated bus service from a stop-events ODX input table (see Gordon et al. (2013), and Dumas (2015) for a discussion of the intricacies of MBTA bus AVL data).

Stop events were included in the "actual" service feed for all scheduled stops based on interpolated times, even if a bus did not actually stop at a given stop. Archived AVL data were unavailable for the Mattapan Trolley and contracted buses, so it was assumed that these services operated with perfect schedule adherence. Commuter rail and ferry services were excluded from the scheduled and actual feeds.

As shown in Table 8.1, the number of actual stop events (between 7 and 9 AM) for the ten days observed was within +3/-9% of the scheduled number of stop events. Additionally, the observed number of trips at the route level was generally within this range of the scheduled number of trips. Negative discrepancies in the number of stop events may be due to dropped trips, short-turning, or incomplete AVL data due to GPS errors.

The generally high schedule adherence, at least at this aggregate level, suggests that large inconsistencies between the routing algorithm's estimates of scheduled and actual travel times may be due to longer-than-scheduled running times or headway irregularity, rather than trips dropped (in actuality or due to missing data).

Table 8.1: Scheduled and observed stop events, by mode

Stop events (7-9 AM)		Light Rail	Subway	Bus
Scheduled (typical weekday)		3,782	2,461	69,256
	10/17 (Mo)	94%	102%	96%
	10/18 (Tu)	93%	97%	92%
	10/19 (We)	94%	102%	94%
	10/20 (Th)	92%	103%	93%
Percent of	10/21 (Fr)	95%	102%	96%
Scheduled	10/24 (Mo)	93%	92%	95%
	10/25 (Tu)	94%	95%	96%
	10/26 (We)	94%	102%	96%
	10/27 (Th)	91%	101%	95%
	10/28 (Fr)	92%	103%	95%

8.3 Results

Fifty-three percent of respondents report public transit as their usual mode for traveling to appointments, and of these, fifty-four percent report arriving late for or missing at least one appointment in the preceding year due to unreliable transit service. The percent of usual transit users reporting at least one late arrival/missed appointment in the preceding year due to unreliable transit (LA/MA) varies substantially between health centers, as shown in Figure 8.1. Whittier St. health center has the lowest LA/MA (37%), and the Greater Roslindale health center has the highest (70%).

Frequency distributions of patients' self-reported travel times to appointments are shown in Figure 8.2. Linear interpolations were assumed between the 15-minute increments used in the survey.
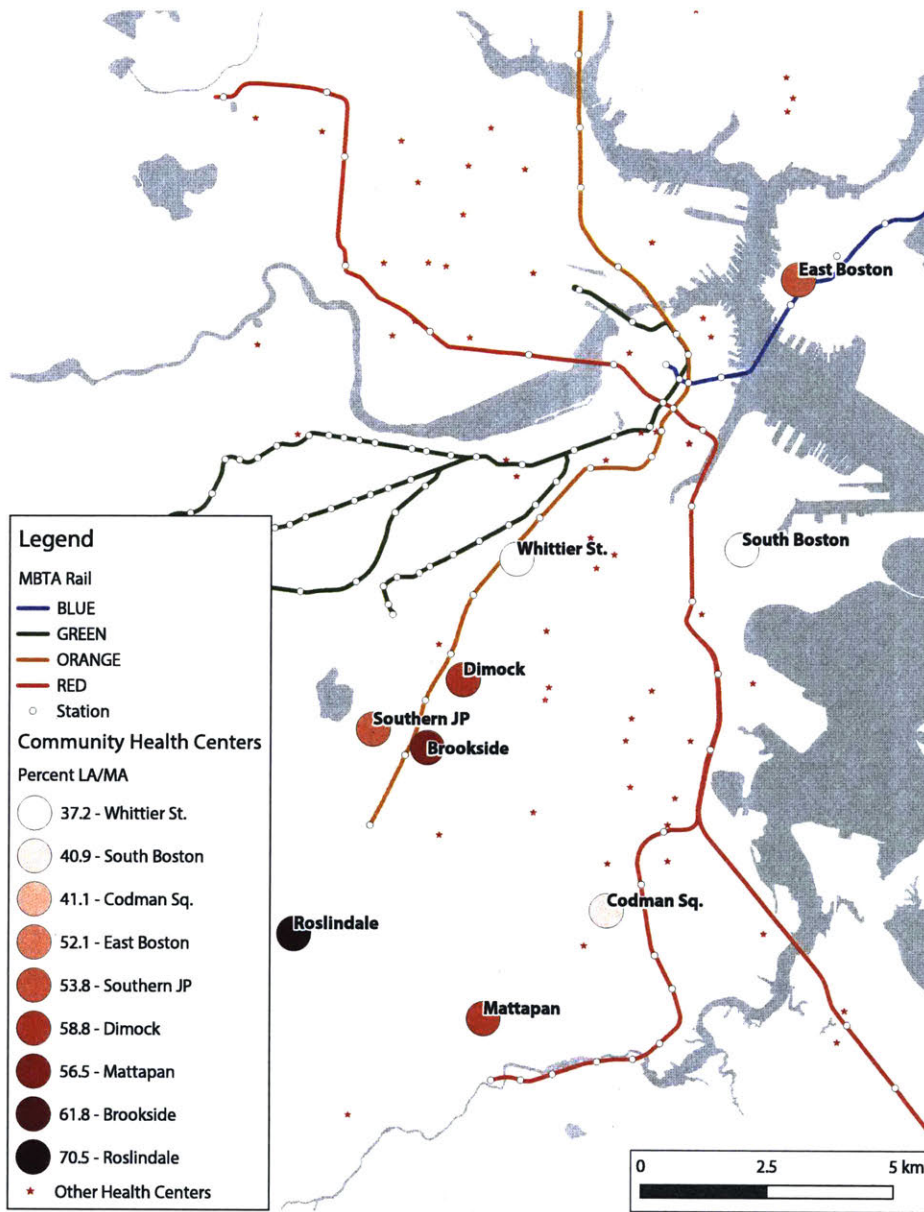
Figure 8.1: Health centers in sample, with percent of patients reporting a recent late arrival/missed appointment due to unreliable transit
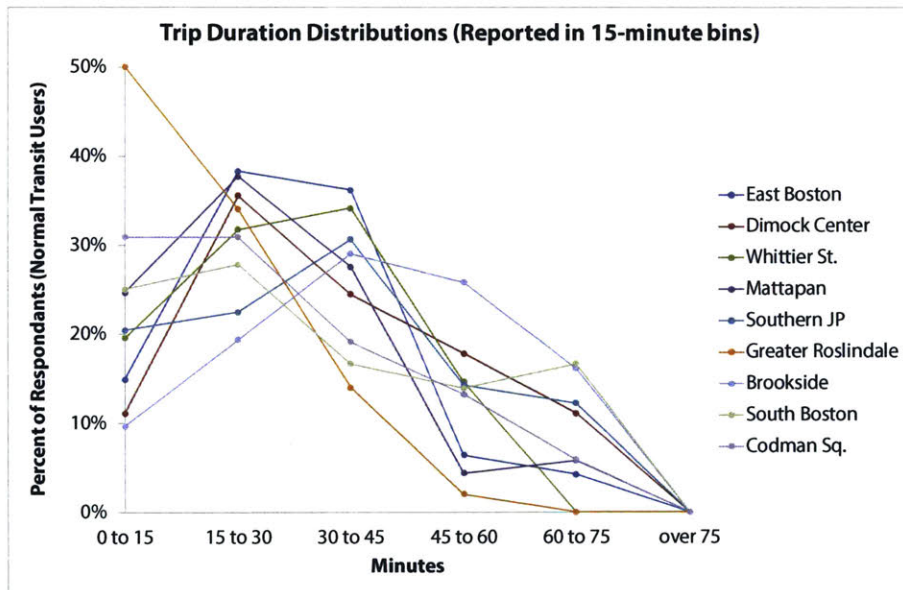
Figure 8.2: Distribution of reported trip durations, by health center

8.3.1 Health center-ZIP code pairs

Figure 8.3 labels the health centers and ZIP codes. Table 8.2 summarizes results for health center-ZIP code pairs with at least 4 respondents in the survey who reported usually taking transit to their appointments. For example, 30 respondents at the East Boston Neighborhood Health Center reported a home location in ZIP code 02128 and transit as their typical mode, and 57% of these respondents reported a LA/MA. These respondents seeded 300 synthetic patients, for whom the scheduled travel time was 10.5 minutes, and the actual time (mean of the daily values, each of which represents the average over 7 to 9 AM on a given day) was 11.2 minutes, a percent difference of 7%. Service variability for this pair across the 10 days of the analysis resulted in a standard deviation of travel time of 0.4 minutes, or a 4% coefficient of variation (COV). Access from ZIP code 02150 was substantially less reliable. All four respondents (100%) from the East Boston-02150 pair reported a LA/MA; average schedule nonconformity for this pair (as measured by percent difference) was 17%, and service variability (as measured by the COV) was 11%.

The largest value of of schedule nonconformity in this table is 26%. The average patient at Brookside Health Center traveling from ZIP Code 02131 would be 6 minutes late on average. Incorporating variability (a standard deviation of 0.9 minutes), a patient would need a buffer approaching 10 minutes longer than scheduled travel times to be reasonably confident of an on-time arrival[4].

The overall correlation coefficient between percent LA/MA and schedule nonconformity (percent difference) in Figure 8.4 is positive but low (0.10), offering weak support for the first of this chapter's hypotheses. Grouping observations by ZIP code also suggests a positive correlation between schedule nonconformity and percent LA/MA. Of the eight ZIP codes with multiple observations in this plot (i.e. from which there were at least four respondents in the survey for multiple health centers), all have positive average slopes. For example, note the points representing connectivity between ZIP code 02150 and the East Boston and Mattapan health centers, or between ZIP code 02121 and the Dimock, Mattapan, and Codman Sq. health centers.

The overall correlation between the percent LA/MA and service variability (COV) in Figure 8.5 is substantially higher (0.49), offering stronger support for the second hypothesis. With the outlying value of the East Boston-02150 pair removed, the correlation coefficient remains positive at 0.36. Of the eight ZIP codes with multiple observations in this plot, six have positive estimated slopes.

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[4]The standard deviation values closely approximate a basic measure of reliability buffer time (RBT) – maximum time minus mean time for the ten days in the sample. The correlation between this value of RBT and the COV values shown in the table is 0.98

Table 8.2: Measures of schedule nonconformity and service variability, for health center-ZIP code pairs

| Health Center	ZIP Code	n	LA/MA	Travel Time (minutes)		Sch. Non-conformity Pct. Diff.	Service Variability	
				Sch.	Mean		Std. Dev.	COV
East Boston	02128	30	57%	10	11	7%	0.4	4%
	02150	4	100%	20	23	17%	2.5	11%
Dimock	02119	10	30%	16	17	4%	0.4	3%
	02121	10	30%	18	21	13%	0.5	3%
	02125	4	75%	33	36	8%	1.1	3%
	02215	4	100%	36	36	-1%	0.8	2%
Whittier St	02120	6	33%	10	10	1%	0.1	0%
	02119	5	60%	17	18	6%	0.3	2%
	02124	5	80%	33	37	12%	0.7	2%
Mattapan	02126	33	52%	15	15	4%	0.2	1%
	02150	13	54%	69	78	14%	2.3	3%
	02121	7	71%	26	32	23%	1.6	5%
	02124	4	75%	25	27	7%	0.5	2%
Southern JP	02130	12	42%	14	15	4%	0.4	3%
	02131	10	60%	25	28	9%	1.1	4%
	02136	5	80%	35	39	13%	1.6	4%
Roslindale	02131	22	64%	12	13	4%	0.2	2%
	02132	12	75%	22	24	7%	1.0	4%
	02136	9	67%	29	31	7%	1.3	4%
	02130	5	60%	24	26	9%	1.1	4%
	02126	4	100%	30	32	9%	1.4	4%
Brookside	02131	6	67%	22	28	26%	0.9	3%
	02130	5	60%	17	17	3%	0.5	3%
South Boston	02127	23	52%	10	11	6%	0.1	1%
Codman Sq.	02124	26	50%	13	14	7%	0.2	2%
	02121	8	38%	20	24	18%	0.6	3%
	02126	4	25%	28	30	6%	0.5	2%
	02131	4	25%	43	49	12%	1.8	4%
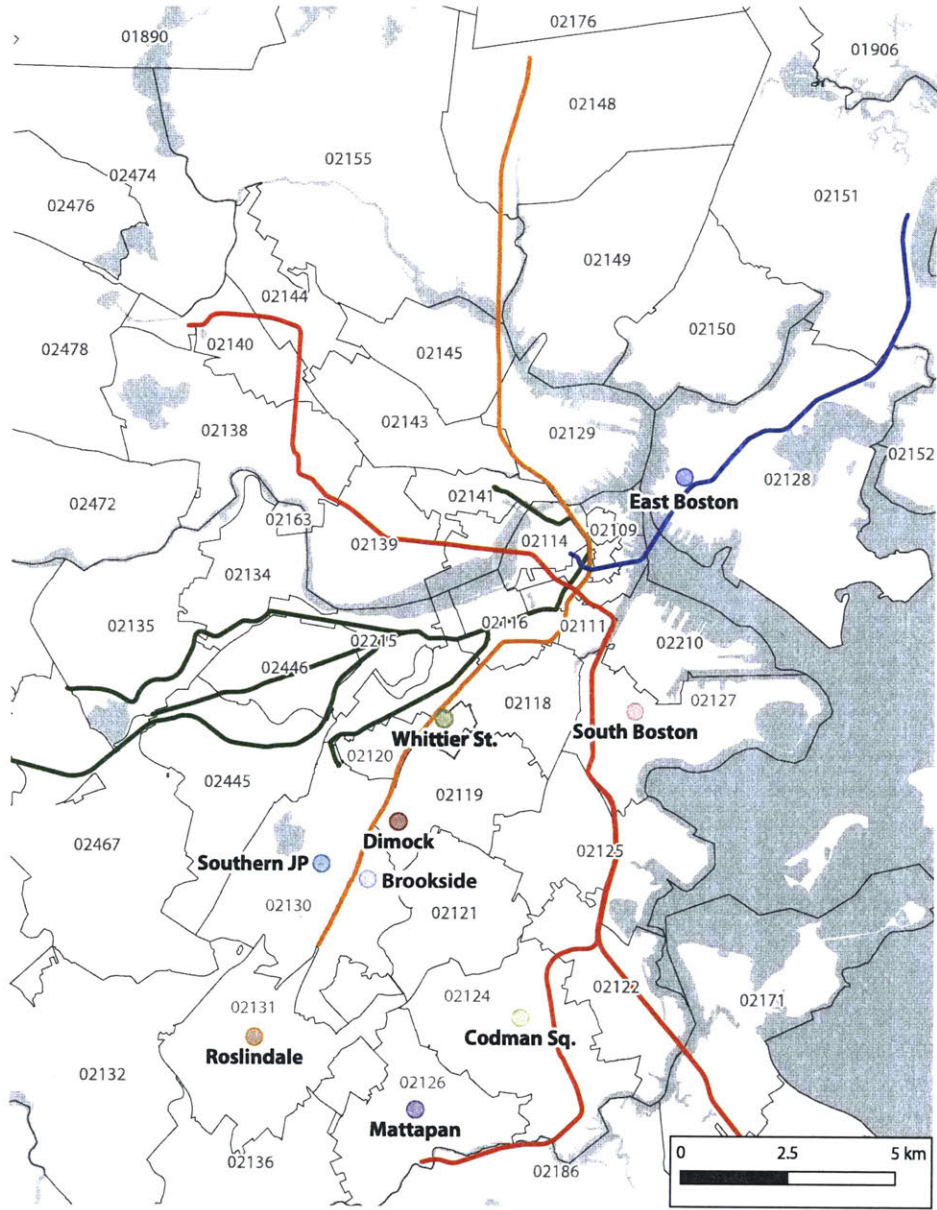
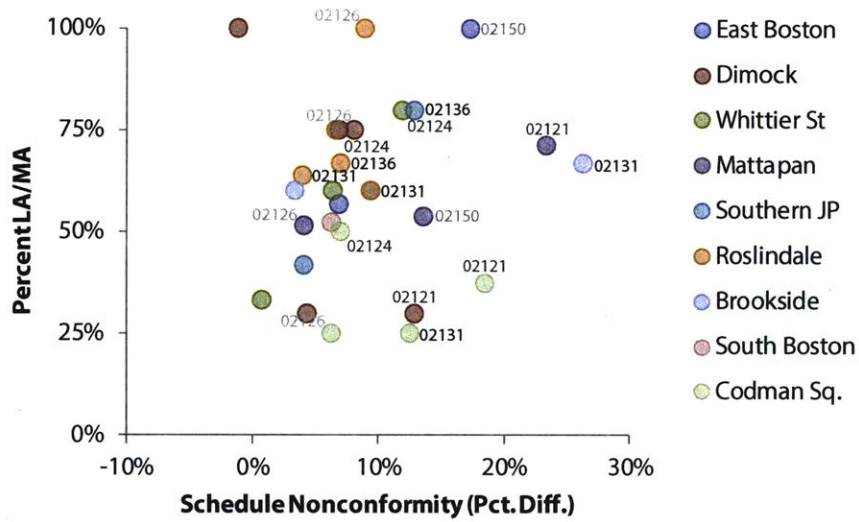Figure 8.3: Community health centers and ZIP code boundaries

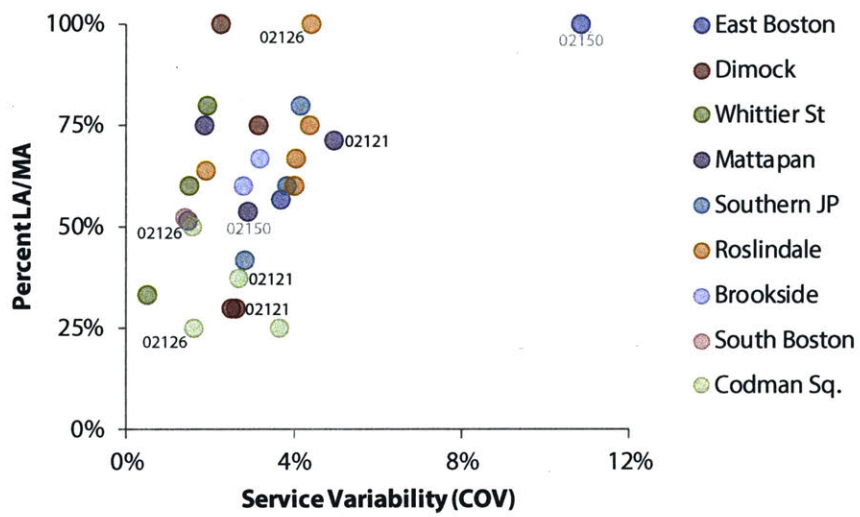Figure 8.4: Percent Late Arrivals/Missed Appointments vs. Schedule Nonconformity

Figure 8.5: Percent Late Arrivals/Missed Appointments vs. Service Variability

Figures 8.6, 8.7, 8.8, and 8.9 depict service for the East Boston Neighborhood Health Center synthetic patients. While the synthetic patients are shown as yellow (reported LA/MA) and blue (no reported LA/MA) dots, in these figures and those that follow, the LA/MA values are randomly assigned to match ZIP-code level proportions; they are not valid at the individual level and should be interpreted only at, or above, the ZIP code level. The catchment area of this health center is predominantly local, with 75% of respondents reporting home locations in the same ZIP code as the health center.

The maps of schedule nonconformity and service variability align with Table 8.2, suggesting for example that residents of ZIP code 02128 have fairly reliable transit access to the health center. The cluster of residents in Chelsea (ZIP code 02150), on the other hand, has much less reliable access to their health center, as discussed above. For example, a cluster of synthetic patients in the southeast quadrant of Chelsea should be reachable within 20 minutes according to the schedule, but many of them would actually be within reach on only one of the days considered (see Figure 8.6)[5]. Most of these patients would experience travel times at least 10% greater than scheduled, with substantial variation across days. Assuming a more stringent departure-time requirement (than a random departure between 7 and 9 AM), and considering crowding and other factors, the level of unreliability that users experience is likely even larger.

The cumulative plot shown in Figure 8.9 shows the number of synthetic patients reachable at travel time cutoffs (τ) up to 75 minutes. Service is quite reliable for most residents within 15 minutes, as suggested by the close correspondence between the scheduled, mean, and actual lines. This close correspondence breaks for values of τ between 15 and 40 minutes. Within 20 minutes, for example,

$a'(t_{ij}^{\text{sch}}) = 76\%$ (the percent of patients that should be within reach based on scheduled service)

$a'(\text{mean}_k[t_{ij}^k]) = 69\%$ (the percent of patients within reach based on mean travel times)

$a'(\text{max}_k[t_{ij}^k]) = 65\%$ (the percent of patients within reach based on the longest travel time for each block)

But as shown in Figure 8.2, only 53% of transit-using patients at the East Boston health center report trip durations less than 30 minutes. This substantial discrepancy may reflect error in the sampling procedure used to generate the synthetic patient residential locations, or tendencies for patients to chain trips and arrive from places other than their homes. It may also suggest that patients experience and perceive longer travel times due to crowding, unpleasant onboard conditions, denied boardings, etc., and that they build significant buffer times into their travel based on awareness of transit's unreliability.

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[5]The Meridian St. drawbridge connects Chelsea and East Boston, but it does not open frequently enough to explain all of the poor transit performance

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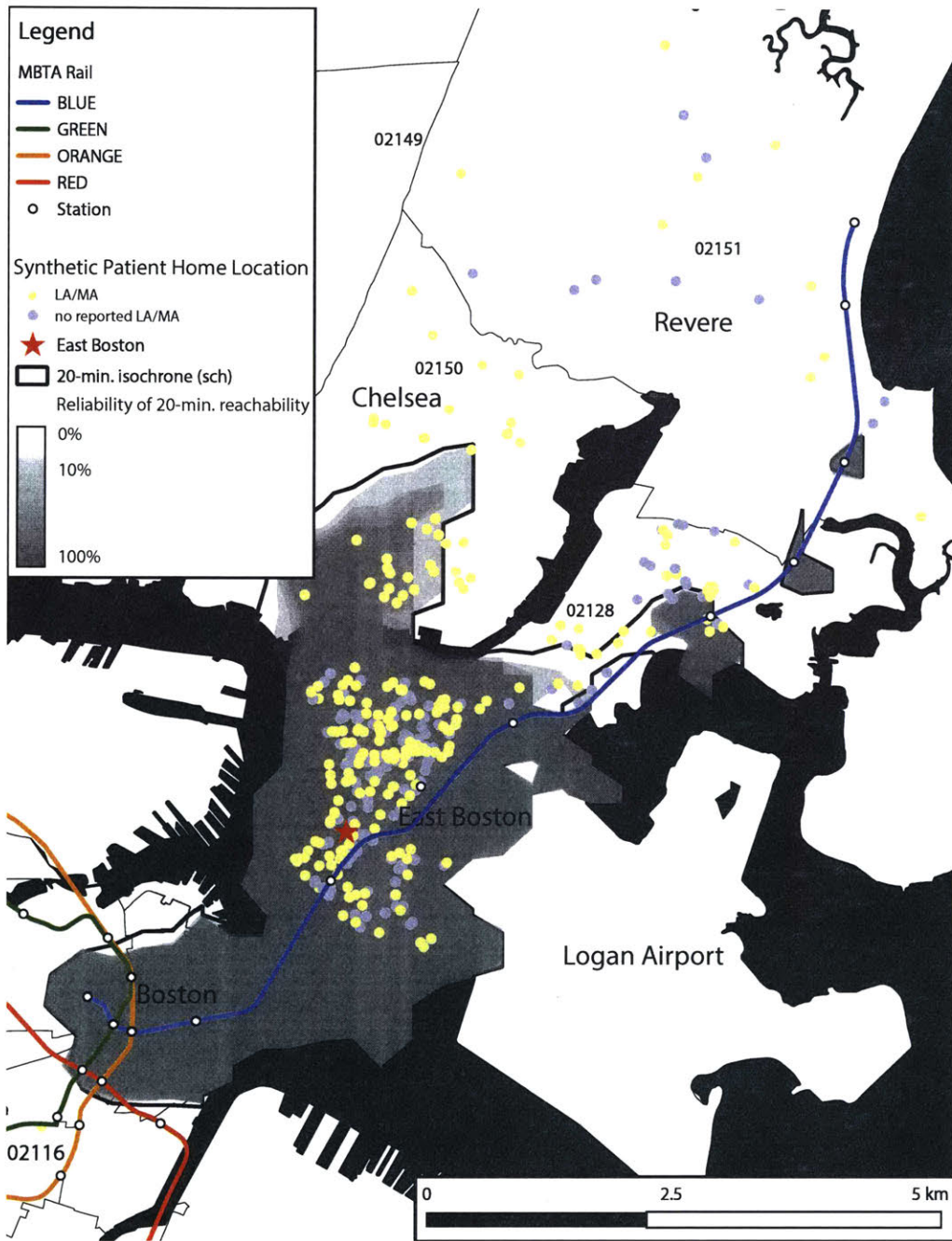
Figure 8.6: 20-minute isochrones from East Boston Neighborhood Health Center

Figure 8.7: Schedule nonconformity, transit to East Boston Neighborhood Health Center

Legend

MBTA Rail
— BLUE
— GREEN
— ORANGE
— RED
  Station

Community Health Centers
★ Other Health Centers
★ East Boston

Service Variability (COV)
  <2 %
  2-4 %
  4-6 %
  6-8 %
  8-10 %
  >10 %

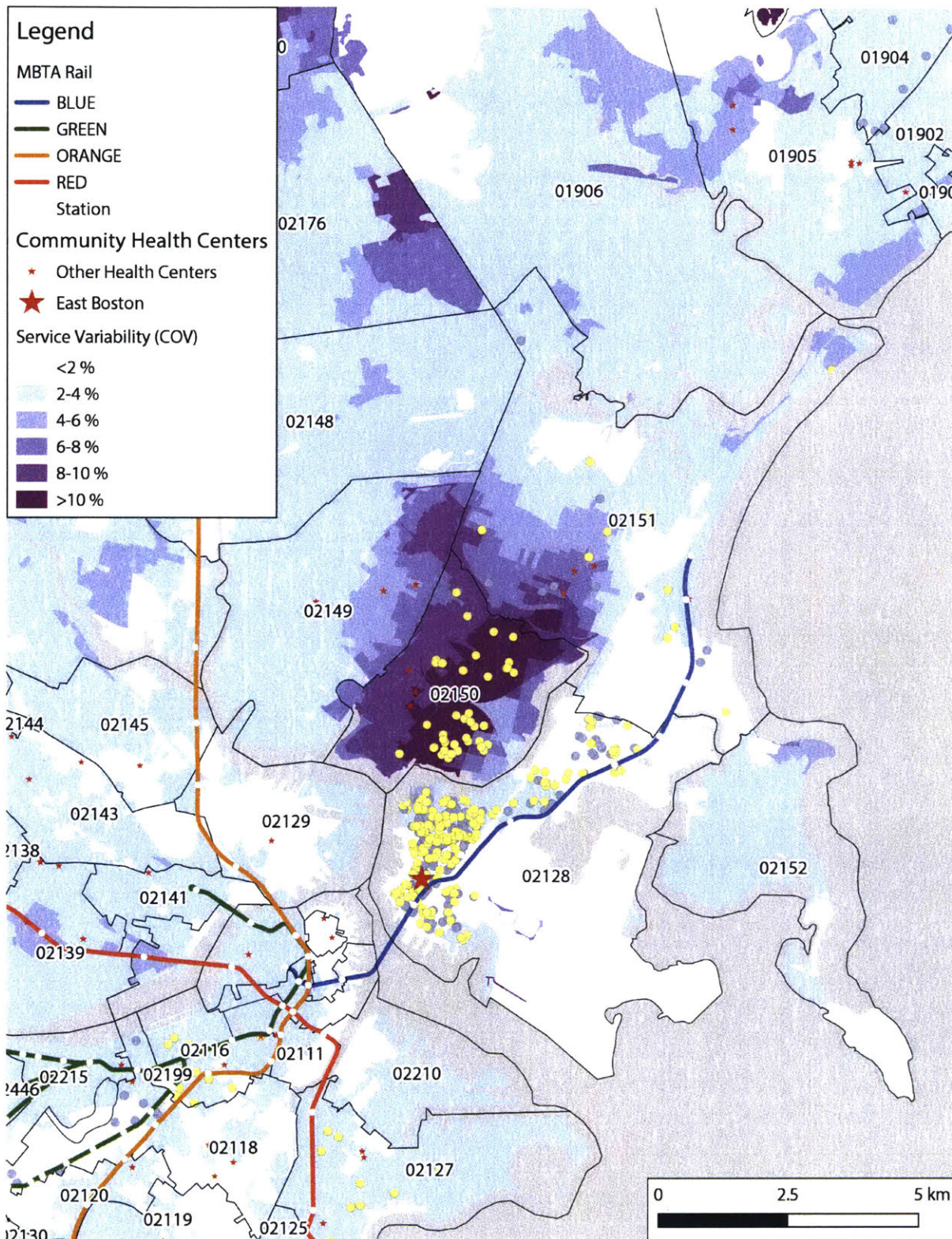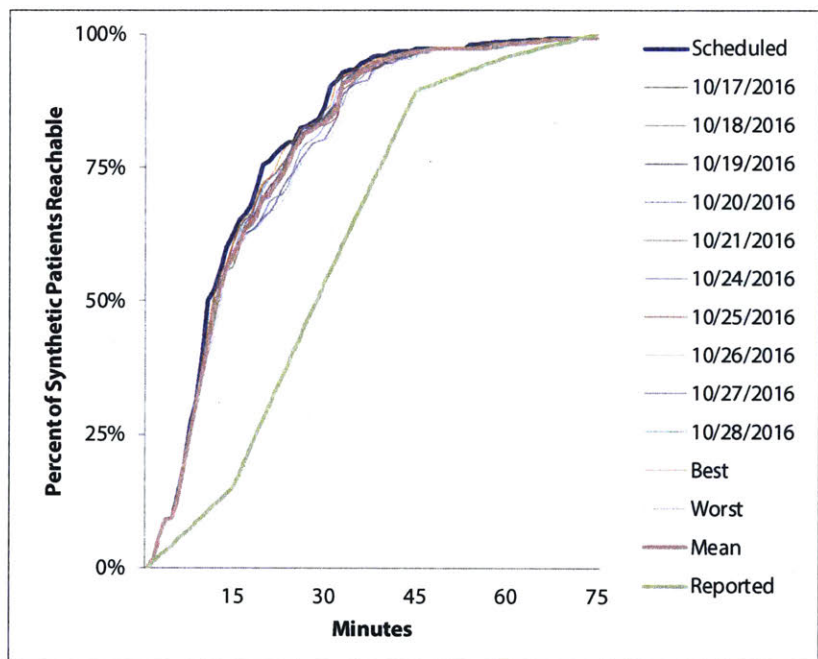Figure 8.8: Service variability, transit to East Boston Neighborhood Health Center

Figure 8.9: Travel time, transit to East Boston Neighborhood Health Center

Figures 8.10 to 8.12 depict service for the synthetic patients generated for the Mattapan Community Health Center. Chronic delays for buses along Blue Hill Ave, running north from Mattapan Square between the Red and Orange Lines, create a swath of blocks where mean travel times exceed scheduled ones by at least 20% (see Figure 8.10). Service variability is not especially severe in this corridor, as indicated by the relatively low COV values (compare Figures 8.8 and Figures 8.11). Bus routes serving this health center are generally much slower than scheduled, but consistently so.

Numerous Mattapan community health center patients reside in Chelsea (ZIP code 02150), despite the large distance. These patients may be employed in Mattapan or have other reasons for regular travel there, making it a convenient healthcare service location for them despite the abundance of other community health centers closer to their residence. Their dislocation may also be a manifestation of the "spatially transitory" nature of low-income workers' residential locations (Boschmann, 2011, p. 671), or of gentrification. The percent LA/MA for these residents is lower than for residents of ZIP codes closer to the health center (e.g. 02121, 02124; see Table 8.2). Relative to the mean travel time of 78 minutes, the standard deviation of 2.3 minutes for travel from ZIP code 02150 results in a coefficient of variation of only 3%[6].

Figures 8.13 to 8.15 depict service for the synthetic patients of the Brookside Community Health Center. Patients of this health center who live in Roslindale and Hyde Park (ZIP codes 02131 and 02136) are subject to substantial schedule nonconformity and intermediate levels of service variability. These figures also highlight potential inadequacy of the synthetic patient generation – one might expect the residents of these ZIP codes to live in the northern tips of the zones, given the relative locations of Brookside and other nearby community health centers. That is, ignoring the availability of other community health centers may lead to samples of patient locations that are biased toward longer travel times. But estimated travel times are generally shorter than the reported ones (note the Reported line in Figure 8.15), suggesting this concern may be unfounded.

Figure 8.16 shows the distribution of travel times for synthetic patients to the Greater Roslindale Community Health Center, which had the highest percent LA/MA of the nine health centers considered. Within 30 minutes,

$a'(t_{ij}^{\text{sch}}) = 76\%$, the percent of patients that should be within reach based on scheduled service.

$a'(\text{mean}_k[t_{ij}^k]) = 71\%$, the percent of patients within reach based on mean travel times.

$a'(\text{max}_k[t_{ij}^k]) = 63\%$, the percent of patients within reach based on the longest travel time for each block.

Based on survey data, 84% of respondents report transit trip durations less than 30 minutes.

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[6]In terms of route choice, it is likely that patients traveling from Chelsea to Mattapan would take the Route 111 bus to the Orange Line, avoiding the aforementioned Meridian St. drawbridge.

Comparing these values for Roslindale to those discussed above for East Boston, the mean is closer to the scheduled, but the worst is further, indicating higher service variability relative to schedule nonconformity. Furthermore, Roslindale patients seem to perceive shorter trip times, while East Boston patients perceive longer trip times than those estimated in this analysis.

Figure 8.10: Schedule nonconformity, transit to Mattapan Community Health Center

Figure 8.11: Service variability, transit to Mattapan Community Health Center

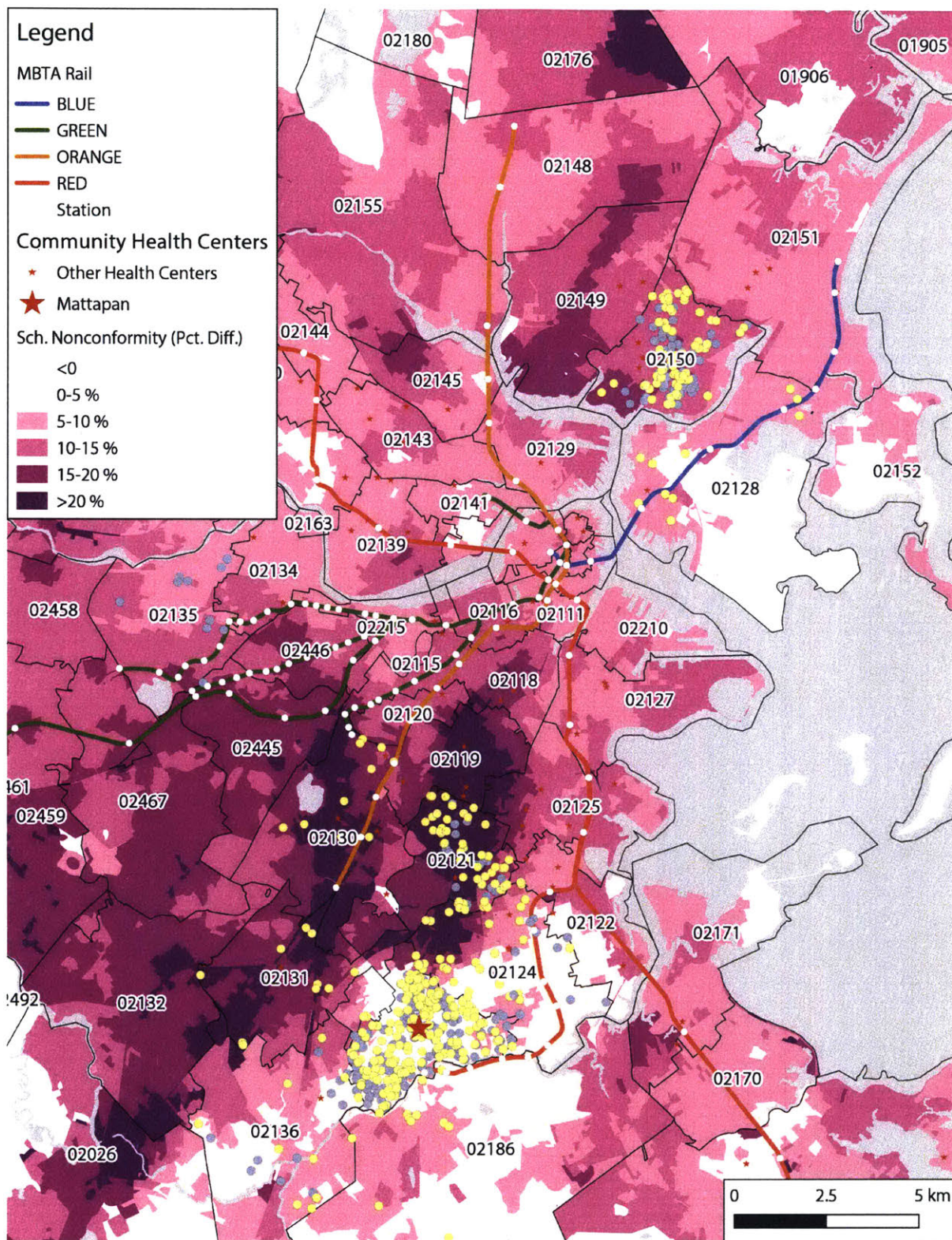Figure 8.12: Travel time, transit to Mattapan Community Health Center

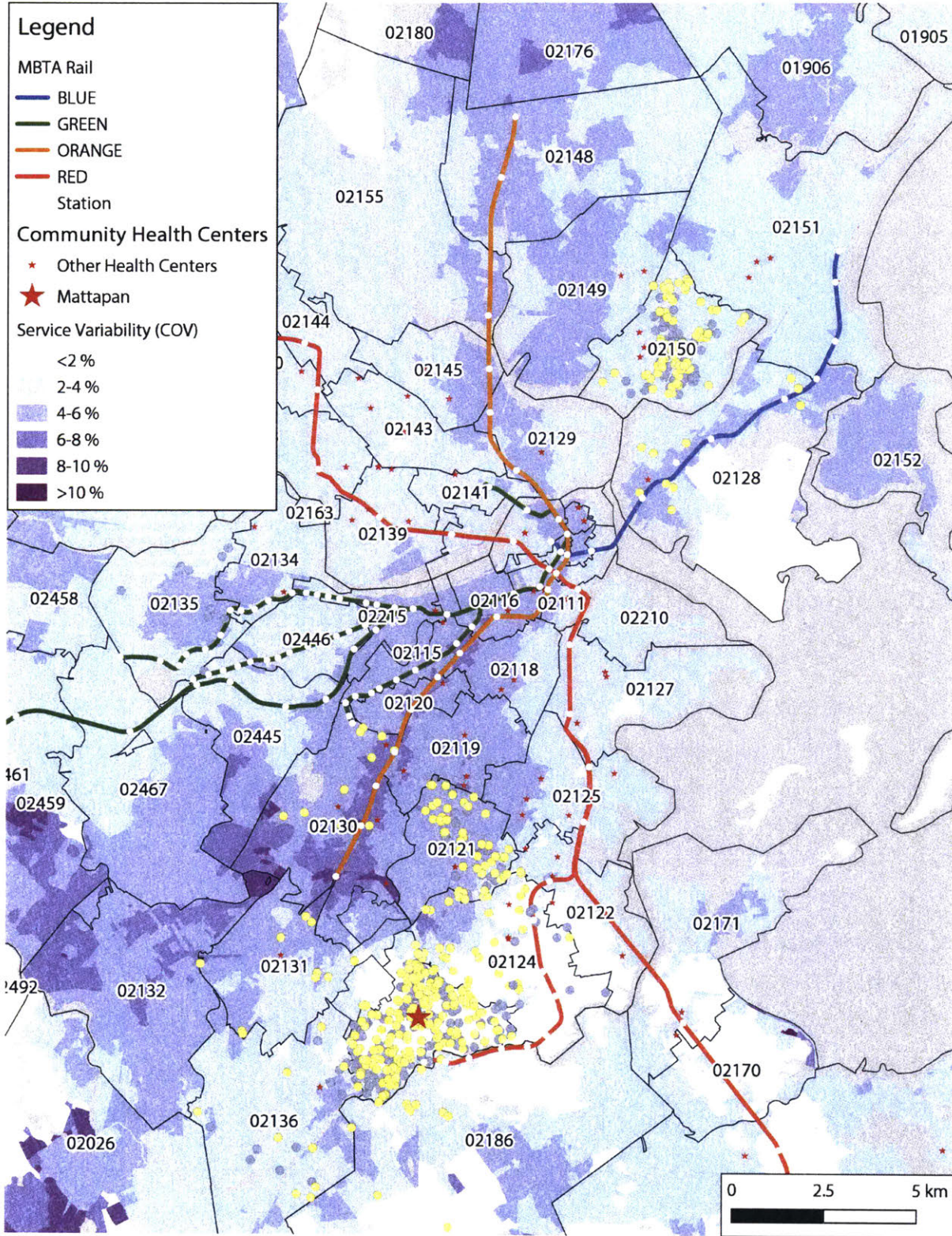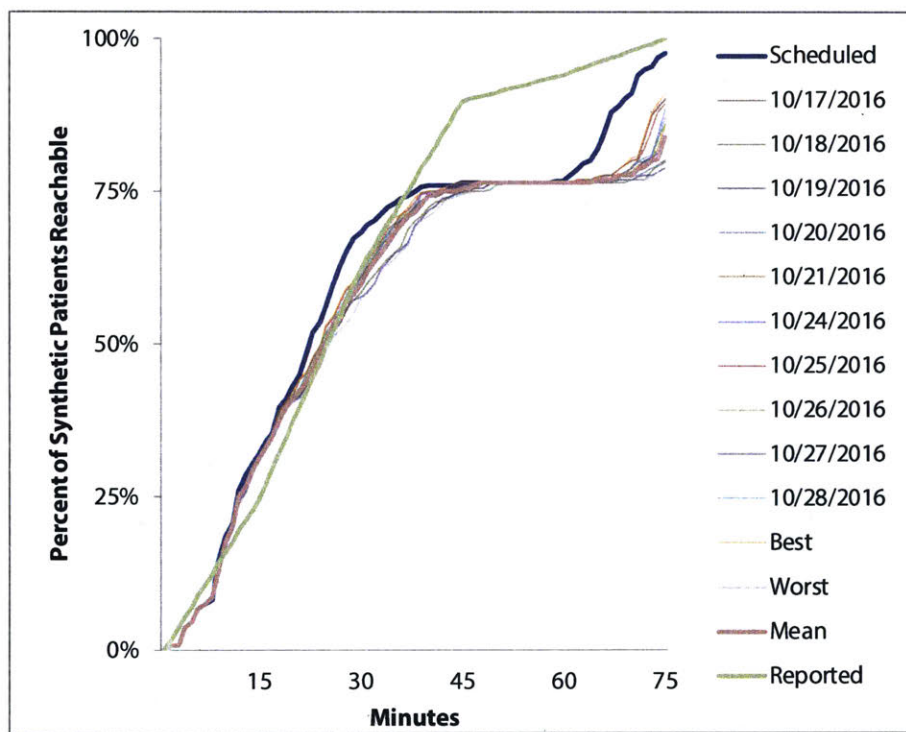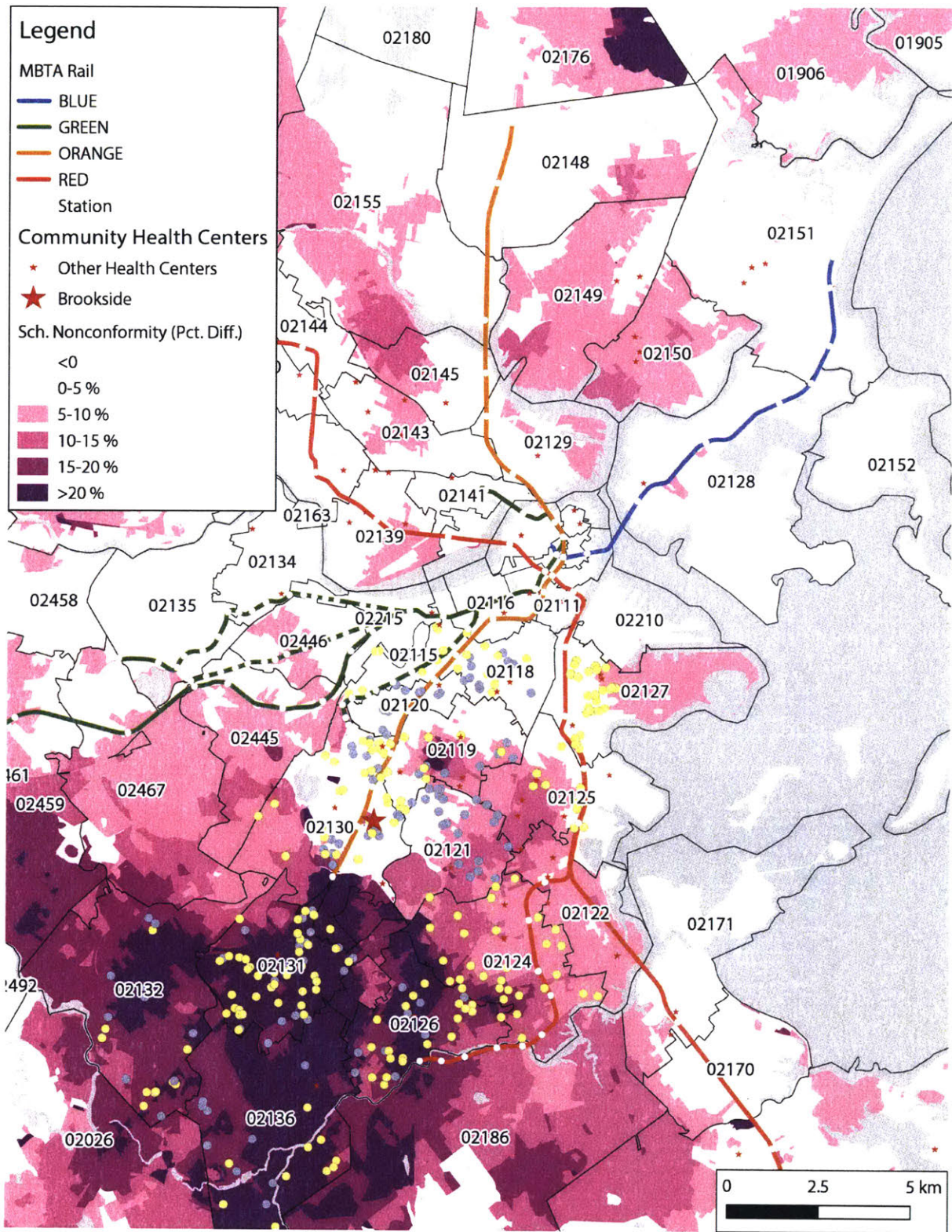Figure 8.13: Schedule nonconformity, transit to Brookside Community Health Center

Figure 8.14: Service variability, transit to Brookside Community Health Center
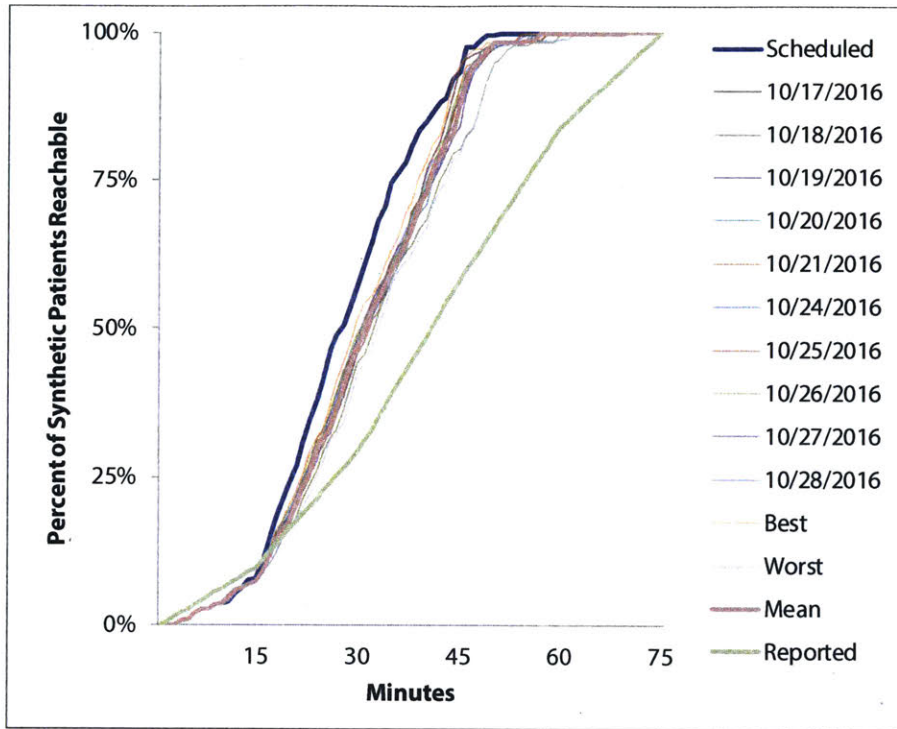
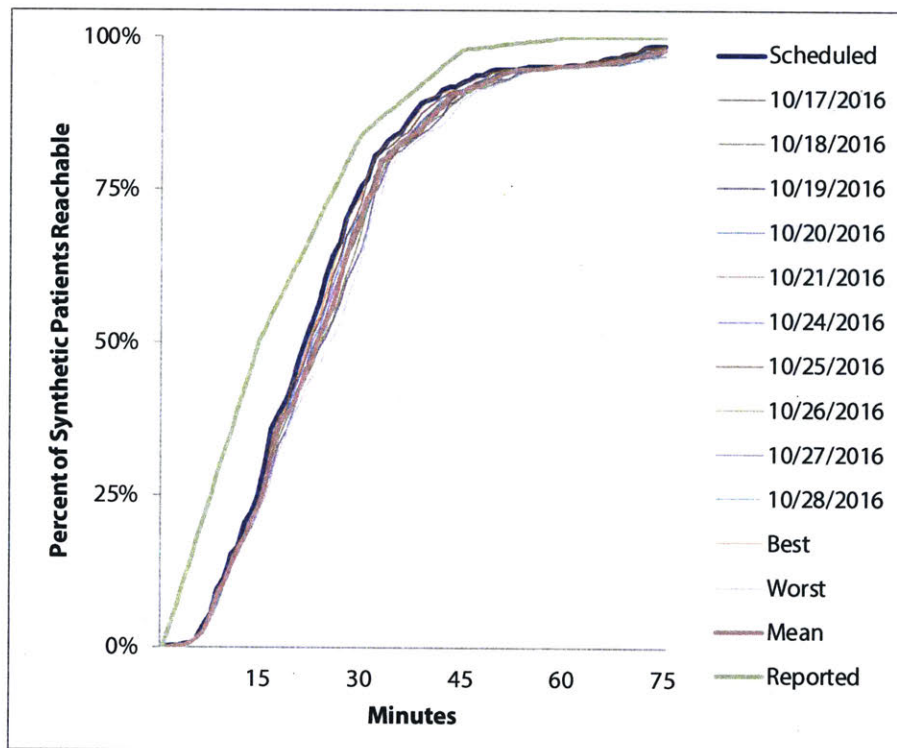Figure 8.15: Travel time, transit to Brookside Community Health Center

Figure 8.16: Travel time, transit to Greater Roslindale Community Health Center

8.3.2 Health center averages

Table 8.3 shows weak negative correlations between schedule nonconformity and LA/MA at the health center level. These signs do not align with the previous findings or the first hypothesis. Correlations with measures of service variability are stronger and positive, aligning with the findings discussed above. This suggests that as day-to-day variability in network level-of-service grows, people are less likely to arrive punctually, as hypothesized.

Table 8.4 uses values based on accessibility to effective residents (i.e. all residents discounted by travel time, as discussed above), rather than average travel times for synthetic patients. The correlations with LA/MA have the same signs and larger magnitudes as those in the preceding table[7].

Table 8.3: Access to synthetic patients, grouped by health center

Travel Time (Mean for synthetic patients)		Whittier St.	South Boston	Codman Sq.	East Boston	Southern JP	Dimock	Mattapan	Brookside	Roslindale	Correlation with LA/MA
	Scheduled	28.9	24.9	26.6	15.4	31.1	29.2	29.5	27.6	24.1	-0.04
Schedule Nonconformity	Mean, Actual	31.7	27.0	29.5	16.6	32.9	30.9	32.9	30.7	25.7	-0.07
	Diff	2.8	2.0	2.8	1.2	1.9	1.7	3.4	3.2	1.5	-0.23
	Pct Diff	10%	8%	11%	8%	6%	6%	12%	11%	6%	-0.27
Service Variability	Std. Dev	0.49	0.28	0.37	0.37	0.59	0.43	0.73	0.57	0.46	0.40
	COV	1.6%	1.1%	1.2%	2.2%	1.8%	1.4%	2.2%	1.9%	1.8%	0.52
Percent LA/MA		37%	41%	41%	52%	54%	58%	57%	62%	70%	1.00

Table 8.4: Access to effective residents, grouped by health center

Effective Residents Accessible (Thousands)		Whittier St.	South Boston	Codman Sq.	East Boston	Southern JP	Dimock	Mattapan	Brookside	Roslindale	Correlation with LA/MA
	Scheduled	17.8	17.0	10.6	13.4	15.5	16.1	8.0	19.9	5.6	-0.39
Schedule Nonconformity	Mean, Actual	15.2	15.3	8.4	11.2	14.2	14.7	5.8	18.6	4.8	-0.29
	Diff	2.6	1.8	2.2	2.2	1.3	1.4	2.1	1.3	0.8	-0.79
	Pct Diff	15%	10%	20%	17%	8%	9%	27%	6%	14%	-0.16
Service Variability	Std. Dev	0.56	0.29	0.31	0.43	0.49	0.50	0.44	0.63	0.30	0.11
	COV	3.7%	1.9%	3.7%	3.9%	3.4%	3.4%	7.5%	3.4%	6.3%	0.54
Percent LA/MA		37%	41%	41%	52%	54%	58%	57%	62%	70%	1.00

Given the levels of aggregation, lack of independence between observations, limited sample size, and possibility of confounding effects related to broader spatial effects, these values

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[7]The correlation coefficient between the time-based and accessibility-based Pct Diff values is 0.49, and the correlation coefficient between the time-based and accessibility-based COV values is 0.65.

should be interpreted with an abundance of caution. They may suggest that as the gap between the mean transit service actually provided to a health center and the level of service implied by schedules grows, the percent of patients who arrive late for or miss appointments decreases, the opposite of the hypotheses discussed above. This finding might also reflect people adapting to consistently underperforming transit and adding extra buffer time to their trips.

Figures 8.17 and 8.18 show the number of effective residents within reach of the Mattapan and Brookside health centers. Because the measure of effective residents incorporates the distributions of reported trip durations, these plots generally resemble the plots of synthetic patient access shown above. Note the plateau between 40 and 60 minutes in Figures 8.12 and 8.17.
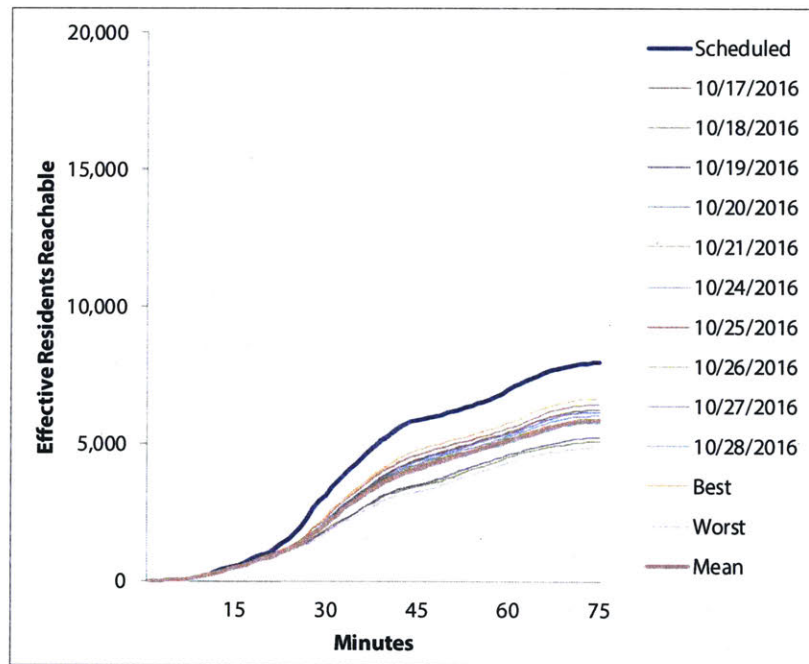
Figure 8.17: Effective residents accessible by transit to Mattapan Community Health Center
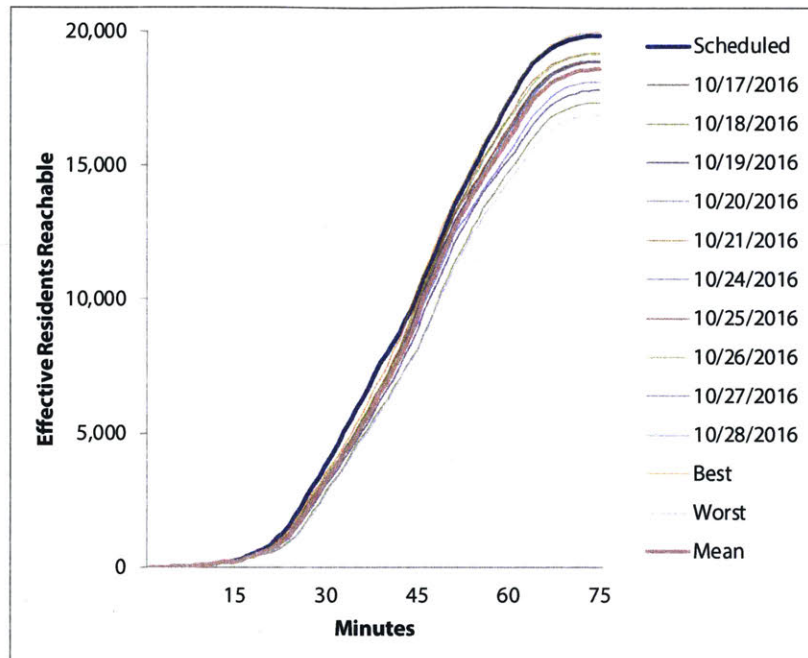
Figure 8.18: Effective residents accessible by transit to Brookside Community Health Center

8.4 Discussion

This chapter used a fine-grained analysis of accessibility to explore links between transit service and healthcare access. The illustrative correlations explored with self-reported late arrivals/missed appointments data suggest that links between the operation of Boston's public transit system and costs imposed on its healthcare system should be investigated further. Unreliable transit may lead to two components of wasted time: extra time that patients build into their trips and knock-on delays health centers face from late arrivals and cancellations. Based on the limited analysis above (e.g. the comparison of different a' values for East Boston and Roslindale), it seems that schedule nonconformity may shift the incidence of wasted time toward the former – users adapt to service that is reliably late if they make the trip frequently enough – while service variability may increase both components of wasted time, and especially the latter. If this is indeed the case, operational and tactical remedies (and public involvement around projects) should focus on reducing service variability, rather than improving speeds alone. This recommendation echoes those discussed in preceding chapters and Stewart et al. (2015).

The difficulties of data access are often cited as a barrier to incorporating wider context and travel needs into assessments of transit network performance. This barrier may be especially high for healthcare access. The methodology tested in this chapter could offer an appropriate balance between meaningful metrics and data requirements. Using only trip duration distributions and Census population counts, adjusted metrics of temporally-aware accessibility to effective residents can be calculated for specific locations (see Figures 8.17

and 8.18); these metrics compare well with more disaggregate approaches and may correlate strongly with outcomes of interest.

An extension of this initial exploratory analysis could consider accessibility over a larger sample of days, including those covering the year preceding the survey implementation, to test for stronger correlations. Sufficiently accurate estimates of actual travel times could be used as a screening tool for providing paratransit and other specialized transportation assistance to patients, based on a recognition of "plastic space" instead of the simple distance criteria that dominate now. GPS traces from paratransit vehicles and other modes taken by patients could also be incorporated.

An improved survey might ask participants to report more precise trip-origin locations (which may or may not be their homes) and more precise estimates of how often they were late by a certain threshold or missed/canceled an appointment. A more robust behavioral approach could match the health center's records of LA/MAs with individual surveys on perceived travel times and issues such as denied boardings. While the methodology discussed in this chapter does not account for such capacity issues, if mesoscopic modeling tools are used to estimate link-level adjustments for crowding and capacity constraints (class D of the adjustments proposed in Chapter 6), these could be incorporated as inputs to the accessibility methods described here.

Part IV

Conclusions

Chapter 9

Summary and Recommendations

The housing crisis is the single biggest barrier to prosperity, growth and fairness facing Londoners today. Whether you're talking to business leaders, local residents, charities or community groups: far and away the biggest issue across the board is London's housing crisis. The city's shortage of decent and affordable homes is causing real misery to millions of Londoners, and damaging London's competitiveness.

– Sadiq Khan
Mayor of London, in 2016

Seemingly overnight, the much-hoped-for urban revival has turned into a new kind of urban crisis... Blue-collar and service workers, along with the poor and disadvantaged... face the direst economic consequences. These groups are being driven out of the superstar cities, and they are being denied the economic opportunities, the services and amenities, and the upward mobility these places have to offer. It's hard to sustain a functional urban economy when teachers, nurses, hospital workers, police officers, firefighters, and restaurant and service workers can no longer afford to live within reasonable commuting distance to their workplaces.

– Richard Florida
The New Urban Crisis

Today's cities are unlocking unprecedented levels of connectivity, due largely to transport infrastructure as well as telecommunications advances. Over time, transport's stretching of plastic urban space has promoted both dislocation (e.g. longer commutes) and a related increase in the value of centrality (of highly accessible locations). Financial capital's globalization allows investors who are thousands of miles from London to shape its built environment without ever setting foot there; they exploit both the placelessness of capital

and the value of central places[1]. Boston is seeing similar patterns of investment and urban revival, so London may offer a preview of things to come[2]. The flip-side of this coin is that millions of people who want to live within easy reach of jobs and amenities in cities like London and Boston cannot afford to do so. The dialectic of centrality and periphery (see Chapter 2) causes "real misery," which transport planning must work to alleviate.

An accessibility framing, supported by rapid computation to enable nearly instantaneous representations of the transport network's role in wider urban space, can support this work. In participatory settings, this framing can structure content spaces that help people understand the sometimes non-intuitive and varying reach that transit provides, and it can structure relational spaces that encourage deliberation and dialog about peoples' needs (see Chapter 3). Transport planning has traditionally focused on the observed or predicted time and volume of tripmakers between nodes in a network. Accessibility planning recognizes that there is value in the potential for people to be able to access different places in a city, even if not all of that potential is actually realized.

9.1 Summary

The first part of this dissertation argued that public transport shapes urban space in less intuitive ways than other modes, masking power relations and complicating public involvement especially if such involvement relies on abstract, static representations of space. A key finding in Part II, focused on a tool for dynamic collaborative accessibility-driven transit planning (CoAXs), is that interactive accessibility mapping can support dialog through rapid computation. But credibility is diminished when represented service does not align with users' experiences, especially of unreliability. Part III makes the case that accessibility measures, especially when adjusted for reliability and matching, correlate with policy outcomes of interest, and that ignoring such measures may lead to perversely biased results. The subsections below briefly summarize the contributions and limitations of this work.

9.1.1 Contributions

Planning just transport systems requires attention to both procedural and substantive equity, that is, of just process and outcome. This double requirement is rooted in a Rawlsian theory of justice, and its urban application by Harvey (1973), who calls for "a just distribution justly arrived at" (see Dikeç (2001)).

Part III of this dissertation shows ways in which urban accessibility benefits are not equitably distributed across different classes of residents and firms. For the case of employment, the

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[1] As Mayor Sadiq Khan put it more succinctly, "The issue is using our homes as gold bricks for investment" (in The Guardian, May 25 2016)

[2] Or not, if successful local opposition to the Boston2024 Olympics bid is indicative.

analysis here suggests that a joint resident-firm bidding process, rather than separate housing and firm location mechanisms, may structure urban accessibility patterns. The contingency of such bidding on wealth and other privileges of initial position may make such inequitable distribution unjust, but a decisive response to this philosophical question is beyond the scope of this analysis.

The methodologies tested here to generate temporally varying reliability metrics, calculated with high geographic resolution (block-level) even in the absence of passenger flows, suggest that unreliability may further impede access to opportunities. If accessibility is its own "sphere of justice" and all residents are entitled to sufficient levels of access to opportunities, as argued by Martens (2017), then the metrics of accessibility chosen should reflect such adjustments. Affordable and reliable transport mobility is a means to upward social mobility[3]. If such upward social mobility is to be the rule rather than the exception in cities, then transit network structure and operations should reduce rather than reinforce inequities in access to employment and services.

If the metrics of accessibility advanced in this dissertation align more meaningfully with residents' everyday concerns, and if they can be the basis of open public participation processes, they may drive more meaningful involvement and just process. The research in Part II of this dissertation implemented pre-test/post-test approaches to quantifying effectiveness of public involvement, as well as measures of participant skepticism, group engagement, and tool interaction. These measures were applied to stakeholder engagement workshops testing accessibility-based tools, but they could be applied to a wider range of public participation processes in urban planning. The finding detailed in Chapter 5, that dialog following an initial framing of accessibility impacts is substantially different from dialog following a point-to-point travel time framing, can inform agency-led public participation as well as advocacy efforts.

9.1.2   Limitations

This research has not robustly addressed larger issues of representation and power. There may be a danger that more sophisticated and engaging modeling and communication tools impart only the illusion of inclusion. Even nominally open data and free open-source software may require expertise and resources to uncover important embedded assumptions. CoAXs limits these assumptions, in part by representing only first-order impacts of changes to transit service and not attempting to predict or simulate land-use/transport interaction, for example. It also allows users to conduct their own sensitivity analyses by varying input parameters like route frequency and speed. This approach suggests a new role for urban planners – identifying relevant parameters and reasonable bounds, then allowing stakeholders to iteratively explore the impact of these parameters and agree on levels to set. But assumptions are likely still embedded in the algorithms underlying the exploration, and defining input parameters and how they can be varied implies the exercise of power.

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[3]The trajectory of London's current Mayor is a testament to these intertwined mobilities.

From an analytical point of view, this research is subject to a number of limitations. The workshops described in Part II had fairly small numbers of participants, limiting the validity of statistical inference. Furthermore, they were conducted in specific, limited contexts, which limits generalizability. Part III focused on formulating and implementing temporally and geographically detailed accessiblity metrics, but the applications described rely on basic correlation analyses, and on limited models that may ignore important confounding effects.

9.2   Putting metrics into practice

Twenty years have passed since Handy and Niemeier (1997) observed "a distinct gap... between the academic literature and the practical application of accessibility measures." Handy (2017) reflects on how scholars of transportation persistently "push favorite ideas without gaining much traction with the rest of the field," and how "accessibility measures are still not standard in planning practice after all this time." This dissertation makes the case for cautious optimism, that we are not bound to be forever stuck in the figurative roundabout she describes[4].

In March 2017, as part of Focus40 Investment Plan for the MBTA, the Massachusetts Department of Transportation debuted an online interactive map of accessibility at a public meeting using a large touchscreen. Built by Conveyal, this tool uses open-source software to help members of the public understand employment access in the Boston region under different investment scenarios, using isochrones and catchment statistics. Earlier in 2017, TfL launched a new version of WebCAT, which allows anyone with internet access to compare isochrones and catchment statistics for current service, planned future projects, depending on requirements for step-free access, etc.

Transit agencies are showing a new openness to adopting the framing and principles of accessibility planning (see Golub et al. (2013)), as well as new tools for calculating and communicating metrics in broadly accessible ways. Specific formulations of evaluative metrics that follow from this openness must come not from technically expert planners, but from co-creative engagement with stakeholders and constituent publics. Some have argued that such external demands will not be forthcoming because accessibility is a "weakly politicized issue" (Pirie, 1981, p. 378), difficult to comprehend and removed from regular firsthand experience (Cervero et al., 1999, p. 1277). But the growing right to the city movement, and its demands for residents to be guaranteed access to a city's amenities, is at its core an embrace of accessibility. This movement is an "effort at spatial reappropriation... [that challenges] what Lefebvre described as a 'bureaucratic society of controlled consumption'" (Soja, 2010, p. 96). Both Soja (2010) and Martens (2017) begin their explorations of spatial and transport justice with the example of the Bus Riders Union in Los Angeles. It is no coincidence that groups like the BRU in LA and the T Riders Union in Boston evolved from making demands about bus service hours and operational reliability to anti-eviction

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[4]Or, to use a more Bostonian metaphor, to be stuck like Charlie on the T

blockades and active participation in the right to the city movement (see Stewart (2010)); they have recognized the land-use/transport nexus of accessibility in ways that presage the adoption of accessibility planning by agencies.

Many of the components for a scaled up co-creative accessibility mapping platform are already in place at agencies. TfL and the MBTA have online trip planners, APIs with real-time data, extensive analysis and archiving of real-time operational and passenger location data, and reporting of performance metrics published to customers. Much of this performance reporting, however, is either too tied to individual behavior (e.g. personalized delay refunds and apologies for incidents issued to Oyster card users in London) or too abstract (e.g. on-time-performance at a line-level, when passengers are likely to care about their overall journey including transfers between lines). If a healthcare center wanted to understand how access to its patients varied over the course of a year, or if an employer wanted to receive alerts about how its employees were affected by a series of disruptions, these transport agencies do not provide the integrated tools to do so, despite having the individual components in place. They provide APIs for online journey planning, through which anyone can enter a single origin and destination to receive information on a potential future trip. It would be a small extension to provide interfaces for online accessibility planning, in which anyone could enter sets of origins or destinations to receive aggregated information about past or planned performance at the network level.

Using this platform, a retailer could upload a spatial layer of different customer demographic groups, understand how a proposed project would change their level of access, and ultimately become a more informed contributor to public deliberation about the project. And, as individual travel time is simply a special case of accessibility, a couple could upload their home location and places of work, then receive weekly performance reports of how much time they wasted in commuting delays, or conversely, how reliable their level of access was for a given commute time (as suggested in Chapters 6 and 8). The tools to automatically and rapidly calculate "actual" accessibility retrospectively on a daily basis, for specific time windows and sets of locations, to provide users with individually-tailored, differentiated representations of space, are already freely available. Putting them to use to co-create understandings of accessibility could improve agency credibility, giving the chance to explain the causes (e.g. history of poor maintenance) and potential solutions (e.g. specific investment plans) for delays through ongoing communication with both individual customers and stakeholders (e.g. corporate transit pass program administrators).

Such a platform could help the public and advocacy groups keep agencies accountable to their needs and claim a right to the city. Instead of having pre-defined metrics ("*the* numbers") by which transport investment decisions are made, advocates could organize to have their specific access needs prioritized, using the same conceptual framing across projects, and a set of evaluative metrics could be agreed upon. Regardless of the specific formulation of metrics, adjustments for matching and actual operations must be made to avoid biases. Agencies could also derive value from customers' data and preferences input to such a platform, especially for research.

While many interventions to increase regional connectivity are outside the "span of control" (in the words of Secretary Pollack of MassDOT) of transportation planning and engineering, this dissertation shows ways for transit at the strategic, tactical, and even operational levels, to contribute directly to (or detract from) accessibility. Transport for London need not compete with Homes for Londoners (the Mayor's initiatives to build new public housing). The goal of both is improved connectivity between Londoners and the opportunities they wish to access, and accessibility makes ways for transport to contribute to this larger goal clear to diverse stakeholders.

Just as both adaptation and mitigation policies can respond to climate change, transport policy and planning can help cities adapt to and mitigate the floods of capital that drive displacement. Strong public transport connectivity can help residents maintain a connection and social ties with their old neighborhoods if they are displaced. More importantly, strategic use of transit investment can help prevent gentrification and displacement from occurring in the first place. The accessibility unlocked by public transport investment increases land values, and effective policies can leverage this value increment for affordable housing. Transport investment in multiple corridors can serve as a relief valve by channeling investment demand to multiple neighborhoods. And if a surge of speculative investment demand cannot be channeled away from certain hotspots, open analysis tools to help residents understand areas at risk for transit-led gentrification can help them target non-transport policies, such as ones favoring community land trusts.

9.3 Future research

This dissertation has focused primarily on accessibility by transit, and first-order changes that ignore longer-term land use changes and impacts on other modes.

9.3.1 Multimodal extensions

Single occupancy vehicles are the primary means of the mobility component of accessibility in the United States[5]. It remains to be seen how this dominance might shift in light of recent advances toward shared, autonomous, and electric vehicles. In any case, cars will continue to play a role for the foreseeable future. The classes of adjustment in subsection 6.3.3 might be one way for future research incorporate accessibility by enabled by different modes.

Better incorporating multimodalism, as well as competition, congestion, and crowding effects

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[5] I heard anecdotally that, for a recent Star Wars premiere, a cinema chain had two leading US properties in terms of ticket sales. The first was Times Square in Manhattan, an iconic central node in New York City's subway system. The second was the Irvine Spectrum, located at the twenty-six lane behemoth Interstate highway interchange known in Orange County as the El Toro Y. Despite vastly different qualities of surrounding metropolitan scale and urban form, the two have access to an approximately equal number moviegoers within a one hour trip, if all modes are considered.

(adjustment classes C and D) are an important area for future research. In many cases, especially near-capacity systems, these adjustments may be more significant, and reinforce, classes A and B explored in this dissertation. For example, if a resident competes with many others for a job, and those other residents use more reliable modes, she may be doubly disadvantaged. Sketch-planning predictions of mode shift, congestion impacts, etc. would also allow for the consideration of wider impacts such as emissions and pollution.

9.3.2 Transit planning and evaluation

Farecard-based calculations of network-level travel times between stops, and how these vary over time, are arguably more useful as actionable guides for short-term operational analysis than the accessibility approaches explored here. But in such calculations, trips to infrequent destinations like medical appointments may be diluted; and the importance of arriving on-time may be higher than for work or other typical trip purposes.

For longer-term planning (e.g of new passengers), the approach taken here, generating a set of network skims to all destinations based on variable travel times, might help inform analyses of uncertain demand patterns (e.g. where revealed passenger travel data are not available).

The discussion of thick labor markets in Chapter 6 suggests that research into the wider economic impacts of transport should expand from considering effective density (largely a function of transport capacity) to considering employment access more broadly (also a function of reach) in project evaluation.

9.3.3 Collaborative planning

Interactive stakeholder engagement workshops like those described here could be conducted in other settings to determine if similar findings hold. More detailed analysis of how interactions, especially varying input parameters, affect participants' engagement and trust, could also be explored.

9.4 Conclusion

While this dissertation has focused on public transport projects, accessibility can change even in the absence of any changes in transportation infrastructure. Growing levels of congestion may erode the accessibility provided by cars, job growth may increase competition for parking, and mobile electronics may create a positive utility of time spent riding instead of driving; these trends would tend to improve the relative accessibility provided by transit and other shared modes. Recognizing this improvement and the potential to leverage changes

in accessibility, forward-thinking regions will promote targeted densification and transport development that further improve multi-modal accessibility. Regions that buy into the false but seductive notion that stopping dense development will keep congestion from getting worse will condemn themselves either to socially unjust and unsustainable hierarchies of exclusive mobility, or widespread and indiscriminate congestion for all.

In metropolitan regions that already have well-developed transit networks, investment is needed to ensure that access is not degraded by growing demand in the joint land-use/transport system. Consider once again the transit reliability surface superimposed on the map in Figure 2.8. This reliability surface responds to a suggestion, from a woman who participated in the debrief discussions for the workshops described in Chapter 4, that isochrones with precisely delineated boundaries were misleading and undermined trust, given the unreliability of bus service in her neighborhood. Transit unreliability in predominantly black neighborhoods imposes additional barriers to access on groups that already face the myriad barriers of gender and race[6]. The fact that Greater Boston's public transport system reinforces these barriers through network design and unreliable operations, and that the region's accessibility system is today not nearly resilient enough to counteract gentrification that drives residents from Roxbury, Dorchester, and Mattapan to places like Chelsea and Everett (see Figure 8.10), deserves a concerted and sustained response.

[6]See, for example, Alexander (2012) for examples of barriers to employment imposed by mass incarceration, and the consequences of missing or arising late to an appointment with a parole or probation officer.

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