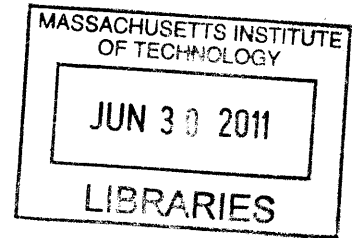


THE TAXICAB AS PUBLIC TRANSPORTATION IN BOSTON

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B.A. in History
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Submitted to the Department of Urban Studies and Planning
in partial fulfillment of the requirements for the degree of

ARCHIVES

Master in City Planning
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2011

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ABSTRACT

This thesis investigates the taxicab and its role as a form of public transportation, using Boston's taxicab system as an opportunity to study the mode's function in the city as well as its relationship to other forms of transportation. In many American cities, the taxicab is an important but frequently overlooked public transportation mode, and it represents a significant opportunity to provide mobility in many places where conventional mass transit cannot do so in a cost-effective manner. Strict regulations guide taxicab operations in most cities, but relatively few exist to directly improve taxicab service or to enhance urban mobility. As a result, economic forces exert a primary influence on taxicab operations that does not necessarily produce socially optimal results.

The central inquiry of this thesis is when and where the taxicab operates as a complement or a substitute to Boston's mass transit system, and which factors appear to affect its fulfillment of each role. I hypothesize that Boston's taxicabs provide better service in locations where transit is also available than in areas with little or no transit access, and I argue that this outcome is not optimal for a variety of reasons. I investigate taxicab activity in Boston by analyzing trip-level data recorded for Boston taxicabs during the past two years, mapping taxicab activity and specifying regression models that illuminate significant relationships between the taxicab, transit access, and other characteristics of the urban environment. I find evidence that the taxicab acts as both a mass transit substitute and complement in Boston, and that this tendency varies by transit line and time of day. I also use these models to infer the existence of unmet demand for taxicab service and suggest interventions to the Boston taxicab system that might better align its service distribution with demand.

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ACKNOWLEDGEMENTS

Writing a thesis is a long, challenging, and often solitary process that has nonetheless been more rewarding because of its arduous nature. For this reason, I am enormously grateful to two groups of people who made the undertaking possible: those who helped me write the thesis and those who provided support in various ways throughout the effort. The former group is quite small but directly responsible for the work you see here, while the latter group is much too large to adequately thank by name.

Among those who helped me write my thesis, none played a more essential role than my advisor, Chris Zegras. His rigor, attention to detail, and willingness to make time to discuss every question that arose helped to shape my broad ideas into arguments and conclusions, and his energetic guidance was a truly enjoyable part of the thesis-writing process. Joe Ferreira, my thesis reader, provided vital direction and enthusiasm as well.

I also owe huge thanks to Mark Cohen at the Hackney Division of the Boston Police Department, who enabled me to access the taxicab data without which my research on this topic could not have begun, and to Rob Goodspeed, whose email last summer sparked my initial interest in studying taxicabs. Nigel Jacob and Vineet Gupta, both with the City of Boston, took time to provide me with the resources I needed to begin this project, and I thank them as well.

The Department of Urban Studies and Planning, of course, has been my home for the past two years. I cannot thank everyone within DUSP I would like to, but Sandy Wellford and Kirsten Greco deserve particular acknowledgement for everything they do. The students, faculty, and staff here have been a wonderful group of people to get to know.

Finally, and most importantly, I thank my family, who has always supported me unconditionally and to whom I cannot possibly express sufficient gratitude on this page.

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I. INTRODUCTION

BACKGROUND OF THE PROBLEM

The informal paths that travelers etch upon unpaved surfaces through repeated traversal, often called desire lines, represent one of the purest visible expressions of travel demand in the urban environment. Pedestrians' optimal routes, if not accommodated by designers or planners, eventually show themselves as the worn tracks that have gradually developed in spaces between streets and sidewalks. Desire lines reveal the shortcomings of a built infrastructure that would ideally provide a direct path for every conceivable trip, offering planners valuable physical clues about how to modify that infrastructure. Although they rarely map demand perfectly, desire lines suggest potential, incremental improvements to an urban transportation network at the pedestrian scale.

The taxicab, at a different scale, traces invisible desire lines upon the urban landscape. As pedestrians take shortcuts across a grassy embankment, taxicabs carry people between points poorly connected by bus or rail transit. Similarly, taxicabs offer faster or more convenient transportation between points that other modes do link. Taxicabs, in other words, facilitate shortcuts for the urban traveler, or the opportunity to increase one's mobility for a higher price. Transportation is a product of both fixed infrastructure and the vehicles (or feet) that move upon that infrastructure, and desire lines demonstrate that where travel demand diverges from any given mode's fixed network, a more flexible solution might arise to compensate for that limitation. The taxicab constitutes one such solution at the urban scale, as a single mode among the full array that collectively form a city's transportation system.

The taxicab's actual and potential contributions to urban mobility are significant. Boston taxicabs make 30,000 to 40,000 daily trips, accounting for at least 1 to 2 percent of all passenger trips in Boston. In certain urban areas, taxicabs provide the only available public transportation (Frankena and Pautler 1984). Operationally, taxicabs exhibit great flexibility: A taxicab can pick up a passenger anywhere in a city and transport him directly to any other location, at any time of day or night (although regulatory constraints may limit this ability). In cities or districts with higher densities of taxicab activity, a passenger can typically hail a cruising taxicab spontaneously with minimal waiting time. A public transportation system should provide mobility between any two points in a city, but trains and bus routes are too far from many origins and destinations to accomplish that objective alone (Alexander 1977); thus, taxicabs augment fixed-route transit in many cities, albeit expensively, as exclusive rides (often consisting of a single passenger) still make up the majority of taxicab trips (Cervero 1997).

More generally, the taxicab constitutes a prevalent form of American paratransit, or transit not operating by fixed route or schedule. Cervero (1997) writes, "Public transit's falling fortunes...stem, to a large degree, from the fact that traditional fixed-route, fixed-schedule, large-vehicle transportation is unable to compete with the private car given today's settlement and travel patterns" (257). Paratransit, including the taxicab, possesses the flexibility to do what mass transit cannot. The opportunity to consider the taxicab as a valuable, specialized component of an urban transit system is an exciting one, and a logical course of action that this thesis will support.

All too often, however, the task of defining the taxicab's precise role within the larger transportation context has received insufficient attention. While cities have recognized the taxicab industry as a vital public amenity and have regulated the industry heavily to

maintain its viability, those regulations reflect taxicabs' relative independence from other urban transportation modes. Gilbert and Samuels (1982) affirm the taxicab's ability to complement fixed-route transit services in both exclusive-ride and shared-ride capacities, but they characterize the taxicab industry as one of the most misunderstood in the United States. They write:

"The taxi industry lacks the technological attraction of rapid transit, light rail, and other more futuristic modes. Nor does it receive the publicity that large-scale bus systems get as a result of their visibility. These reasons have no doubt made planners, public officials, and students of urban transportation content to ignore taxi ordinances while they focused on such programs as area rapid-transit systems, authorities, and developmental technologies."

(4)

Nearly two decades before this assessment, Meyer et al. (1965) noted that urban travel in most American cities was dominated by "high-quality private automobile or by bus or rail transit of fairly low quality. There are few in between, such as taxis, jitneys, or limousines" (355). They blamed the taxicab's limited effectiveness as public transportation on regulations that had driven fares upward by restricting supply. Both of these critiques remain relevant today. Little evidence suggests that the taxicab industry in most major American cities has changed fundamentally in recent decades.

The taxicab's relationship to other forms of public transportation has grown less apparent over time but was once quite clear. The taxicab's divergence from fixed-route transit in the United States, however, has produced a regulated but still private (and profitable) industry in the former instance and a heavily-subsidized public sector operation in the latter, with quite different attitudes and agendas accompanying each.

Both the taxicab and mass transit evolved from a common ancestor, the horse-drawn hackney carriage, which first appeared in seventeenth-century Paris and London. Operationally, the hackney shared many characteristics with the modern taxicab, but fixed-route hackney operations, or omnibuses, emerged in the nineteenth century and “began an evolution which was to separate (fixed-route transit) from the demand-responsive services, the taxicab and its predecessors” (Gilbert and Samuels 1982, 17). The contemporary differences between the two modes reinforce entirely separate notions about the role each mode might play in the city and the degree to which planners or the public can even dictate such roles.

The taxicab industry that operates today in U.S. cities remains a largely unplanned and private enterprise. Many cities still set the parameters for taxicab service through regulations that restrict market entry and standardize fares, although several cities have eliminated such regulations (Cervero 1997). Aside from the objectives of protecting customers and preventing excessive competition, current taxicab regulations reveal few coherent goals for the taxicab’s role in the urban transportation system, and in general they do not articulate a vision for the industry. Opportunities for such interventions do exist, however, including shared-ride services or more widespread taxicab stands.

Recent evidence suggests that major U.S. cities have begun taking a more active approach to defining the taxicab’s proper role in the urban context and have developed plans to encourage that role. In 2008, the City of Boston announced that “a comprehensive set of new rules and regulations will be issued to the Boston taxi industry in an effort to drastically improve the quality of taxi service in the City of Boston.” These included an upgrade to hybrid vehicles, universal credit card processing capabilities, and other amenities that would benefit customers as well as taxi drivers.

The Mayor's Office of New Urban Mechanics in Boston states on its website that "taxis are one component of the City's extensive transportation system" before describing additional projects in development that will improve taxicab hailing and the choice of new taxicab stand locations. Likewise, a 2007 study of New York City's taxicab system by the Design Trust for Public Space and the New York City Taxi & Limousine Commission summarized the taxicab's role there as follows:

"New York's taxi services form a system—a network of interactions between people, vehicles, and the city itself. The focus of this publication is on understanding those interactions and then considering what feasible, incremental changes might improve taxi services to the benefit of the entire system." (9)

That study, titled *Taxi 07: Roads Forward*, accompanied a program called Taxi 07 that began as "a collaborative starting point to take a fresh look at redefining the taxi—from both a functional and aesthetic standpoint—to complement our beautifully transformed metropolis" (5). These efforts, led by the agencies that deal with New York taxicabs most directly, reflect comprehensive visions that rarely accompanied the taxicab industry in decades past.

Along with more ambitious efforts to understand and plan for their taxicab systems, cities have gained access to data that enable the pursuit of both aims in entirely new ways. Technological developments within the taxicab industry account for much of this new information, such as improved credit card payment systems that yield detailed records of taxicabs' locations, travel times, and fares. Similarly, advances in dispatching technology are streamlining the operational efficiency of taxicabs. Outside of the taxicab industry itself, cellular phone records and similar data sources have begun providing

great insight into urban mobility patterns. Liu et al. (2009) note that “as city-wide urban infrastructures such as buses, taxis, subways, public utilities, and roads become digital, these datasets can (be) used as framework(s) for tracking flows through space and time” (1). The aforementioned examples from Boston and New York both indicate the centrality of newly-available data to their proposed interventions, but planners and academics have only begun to realize the possibilities that these vast resources enable.

The taxicab is a vitally important transportation mode in many different types of U.S. cities. Powerful new tools have recently emerged to answer questions about the taxicab that would previously have entailed prohibitive costs and challenges, and cities now have the opportunity to set more ambitious goals for their taxicabs because of the deeper insight that such data might facilitate. The taxicab’s once-invisible desire lines, through these records, can become visible. The beginning of this section described the taxicab’s enormous potential as a flexible and adaptable component of the urban transportation system, and the rest of this thesis will investigate the degree to which that potential is currently being realized.

STATEMENT OF THE PROBLEM

If the taxicab should, in fact, fulfill a specific purpose or set of purposes—an idea the first part of this thesis explores in depth—then a nuanced understanding of how the taxicab currently functions in cities is a necessary prerequisite to understanding how its role might change. This thesis will examine the taxicab system of one major U.S. city, Boston, to assess the taxicab’s recent performance there and draw conclusions that have relevance for other cities as well. The central question of this thesis is the following: *How is taxicab activity distributed throughout Boston, and does supply appear to match demand effectively?* More specifically, I inquire what taxicab activity can tell us

about total demand for taxicab travel by investigating the factors that appear to influence (or at least exhibit a significant correlation with) taxicab supply and demand in Boston, as manifested in the form of trips that actually occur. The relationships I observe between Boston's taxicab activity and its transit network, in particular, represent vital clues about how taxicab supply and demand relate to overall supply and demand for public transportation in the city, and how the taxicab functions as one component of that larger urban transportation system. Complete records of individual trips by Boston taxicabs, which the City has collected for the past two years, enable the mapping and regression analysis of taxicab activity that will help to answer to these questions.

Taxicab activity, in this research, refers to passenger trips by taxicab: pickups, drop-offs, and trip characteristics including fares and travel times. A trip by taxicab represents an instance of *realized travel demand*, in contrast to a desired trip that did not actually happen due to excessive cost, travel time, or another limitation. Because the desire for travel typically precedes mode choice, I assume that a realized taxicab trip reflects the taxicab's greater utility in comparison to other available modes for that particular trip. Assessing the taxicab's contribution to overall mobility throughout Boston using data that only show realized demand is a challenge that this thesis must address in answering its primary questions.

Boston's realized taxicab activity, like that of any mode, is unevenly distributed throughout the city. The knowledge that taxicab activity is spatially "lumpy" logically precedes another fact: Certain places in Boston or in any other city will enjoy more taxicab service while others will have less. A multitude of factors, including land use intensity, population, and availability of alternative modes, contribute to this variation by

influencing taxicab supply or demand. These factors potentially explain high concentrations of taxicab activity in certain places as well as sparse activity in other areas.

The uneven distribution of taxicab trips gains particular relevance in light of the taxicab's aforementioned function as public transportation. Considered independently of other modes, the significance of the taxicab's uneven service distribution remains somewhat unclear. Considered as one component of a multimodal system, however, this condition raises another important question: Does the taxicab system complement other modes by providing relatively better mobility where those other modes do not, or does it act as a substitute for those modes by duplicating their service patterns? A high degree of operational flexibility equips taxicabs to do what fixed-route transit inherently cannot, operating in the spatial and temporal gaps between the latter system's predetermined routes and schedules as demand for such travel arises.

If the taxicab fails to fill gaps in the accessibility pattern that Boston's other transportation modes create, it may not be serving its optimal purpose. Levinson and Krizek (2008) write, "Competition between modes, under certain circumstances (without subsidies for positive feedback industries, and without penalties for negative externalities), may result in socially sub-optimal results" (113). If taxicabs primarily reproduce mass transit routes, for example, the two modes are, to some degree, competing for riders. Because Boston limits its taxicab supply using medallions, more taxicab service in certain parts of the city can mean less service in other parts. As discussed above, taxicabs are uniquely suited to serve places that are less accessible by other modes, so disproportionate taxicab activity in Boston's *most accessible* areas, all else being equal, would suggest a suboptimal outcome similar to what Levinson and

Krizek describe. Taxicab activity need not distribute itself evenly throughout Boston, of course, since demand itself is not evenly distributed, but high-demand locations with few alternatives will ideally reap the benefits of good taxicab service.

This thesis examines the distribution of taxicab activity in Boston, assessing the degree to which taxicab activity either duplicates other modes or fills the gaps they create. Having done so, it attempts to infer whether pockets of unmet demand exist that the taxicab is potentially best suited to serve. While the available data offer detailed knowledge of *realized demand* or taxicab activity in Boston, unmet demand can only be estimated. To answer the questions posed here, then, I infer overall demand by observing the incidence of realized demand in Boston and the spatial characteristics of urban areas that appear to influence it, along with the availability of other modes. I use regression analysis of taxicab trip data to assess which factors impact taxicab activity in Boston, and to what degree.

The following hypothesis guides the analysis just described: Boston taxicabs duplicate other modes in highly accessible areas more commonly than they fill accessibility gaps in the city's transportation system, all else being equal. That is, the taxicab serves as a substitute for these modes more than it should. This hypothesis proceeds from the expectation that Boston's most accessible areas, as defined here, will contain greater concentrations of potential taxicab passengers than their less accessible equivalents. The perceived higher probability of quickly finding a passenger in such areas will attract more taxicabs, thereby increasing the supply of taxicabs in those places. It is unlikely that this supply distribution proportionally matches that of demand.

By answering the central question of how Boston's taxicab activity is distributed, this thesis will provide planners, policymakers, and the taxicab industry itself with useful

tools for improving taxicab service in Boston. Since the data this thesis employs to answer its questions have only recently become available, few studies in Boston or elsewhere have attempted to analyze taxicab activity at such a fine spatial resolution. By determining which urban areas receive high levels of taxicab service and which do not, and by identifying underserved parts of the city through the lens of the multimodal public transportation system, targeted efforts might address the system's precise shortcomings instead of its aggregate conditions.

SCOPE OF ANALYSIS

The questions posed above require a careful, rigorous approach and a precise definition of analytical scope. These questions are substantial and broad, but there also exist many related questions which this thesis will not address, as some would require entire theses of their own. Additionally, the nature of the available data creates certain limitations though it facilitates previously unavailable insight.

This thesis restricts its direct inquiry to taxicabs licensed by the City of Boston (although neighboring towns will provide important context) and to trips that occurred in 2010 and 2011. The available trip-level data on pickup and drop-off locations and fares have only been collected comprehensively and made available for taxicabs licensed in Boston, and the technology that enables that data collection was only widely installed two years ago. Of course, other municipalities' taxicabs often transport passengers to Boston and Boston taxicabs often carry passengers to suburban destinations. This is a necessary limitation of the data, although the data set comprises virtually all licensed taxicab trips that begin as well as end in Boston. That subset provides a sufficiently complete sample to answer my central research questions but my analysis will acknowledge the uncertainty surrounding other trip types and draw conclusions accordingly.

This analysis does not investigate trip purposes or user characteristics in detail, focusing instead on characteristics of *locations* within Boston as well as a few specific taxicab trip characteristics. The relevant spatial characteristics here include measures of physical urban form, modal accessibility, land use, and socioeconomic characteristics; furthermore, many of those characteristics will imply qualities of the users that board taxicabs in those areas. The characteristics of taxicab trips—origin, destination, fare, and travel time—are the phenomena to be explained rather than explanatory variables themselves. The purpose of this thesis is to answer questions about where taxicabs contribute to accessibility and where they do not, rather than why taxicab trips are made or who, precisely, is making them. Accessibility is a characteristic of places, not people (although a place’s accessibility can vary from person to person), and this research reflects that.

While Boston’s spatial characteristics and multimodal transportation system constitute the independent variables in this analysis, the taxicab trips themselves are the dependent variables. This approach reflects the underlying theory that variations in the urban environment influence and even determine where taxicabs circulate and where trips occur.

CHAPTER SUMMARY

The next chapter of this thesis establishes the taxicab’s role in the urban transportation system, beginning with a precise definition of the mode as discussed herein. A summary of the taxicab’s operating characteristics, constraints, and historical evolution precede a discussion of the taxicab’s purpose in the urban context, along with a consideration of how regulatory measures might encourage the industry to fulfill these purposes. A description of the taxicab’s ability to both complement and supplement

other transportation modes concludes this discussion. The third chapter introduces the specific case of Boston and the particularities of its taxicab system, situating this case within the context established in Chapter Two. The fourth chapter introduces the analytical methodology by which I investigate the primary research questions of this thesis: How does taxicab activity distribute itself throughout Boston, and to what degree does the taxicab complement mass transit or substitute for it? A preliminary definition of realized demand, and how it differs from total demand, provides a necessary preface to a detailed outline of the data and methodology that my analysis employs. After establishing the scope of the study—Boston taxicab trips during the past year—and describing the data that reflect those trips, the remainder of Chapter Four summarizes the analytical methodology itself in three separate phases. Chapter Five reviews the findings of that analysis, while Chapter Six concludes with suggestions of measures by which the City might improve taxicab service (and taxicab data) in Boston, given the mode’s public transportation role.

II. THE TAXICAB'S ROLE IN URBAN TRANSPORTATION

This chapter discusses the taxicab's role in the urban transportation system, introducing the idea that the taxicab is an important form of public transportation. The first section of this chapter defines the taxicab as a transportation mode and summarizes its historical development. The second section establishes the taxicab's role in urban transportation through a review of existing literature. The third section examines whom the taxicab serves through the lens of economics, while the fourth section discusses the taxicab system's ability to function as both a mass transit substitute and complement—a concept that is central to the analysis that follows.

A. Definition of the taxicab and public transportation

Before reviewing and evaluating various perspectives on the taxicab industry, a precise definition of the research subject is necessary. "Taxicab" is a flexible term for a mode of transportation that can assume many forms, and these are often distinguished by slight operational nuances. Fortunately, the particular scope of this thesis allows a more formal definition, as provided by the Boston Police Department (2008):

“A vehicle used or designed to be used for the conveyance of persons for hire¹ from place to place within the city of Boston, except a street or elevated railway car or a trackless trolley vehicle...or a motor vehicle, known as a jitney, operated in the manner and for the purposes set forth in Massachusetts General Laws chapter 159 A, or a sight-seeing automobile...”

Any vehicles fitting this description fall within the regulatory scope of the Boston Police Department’s Hackney Carriage Unit and require a license, or medallion, to operate. This thesis will adhere to the same definition in its analysis of Boston’s taxicab system, although discussing taxicabs beyond Boston requires a less rigid definition.

More generally, the taxicab tends to exhibit a set of agreed-upon operational characteristics, although Cervero (1997) warns that precise definitions are elusive: “While there are always dangers in attempting to bound in what many ways is a continuum of paratransit services, boundaries are nonetheless drawn...to help sift through and organize the evidence” (31). Cities like Boston, which must formally define the taxicab in order to regulate it, also draw such boundaries, artificial though they may be, and strict regulations can suppress the very existence of modes residing near taxicabs on Cervero’s continuum. Boston’s definition, above, resolves the predicament

¹ A vehicle for hire, as the term is commonly used by regulators, implies operation by a driver and not the customer, excluding car rentals and carsharing from this definition.

by stating what a taxicab is *not*, within the broad category of vehicles that offer passenger transportation for hire.

Licensing offers the least ambiguous criterion for defining the taxicab in the United States, but operational characteristics provide a more useful understanding of what a taxicab actually is. Perhaps due to public familiarity with the taxicab and the clarity that licensing establishes, the literature contains few efforts to define the mode by its characteristics. Every definition shares certain traits, however: A taxicab is always a for-hire, motorized vehicle that provides primarily local passenger transportation. Additionally, taxicabs are demand responsive: Whether hailed on the street, dispatched by radio, hired at a taxicab stand, or contracted for service, the taxicab travels directly between customers' desired origins and destinations and not along predetermined routes and schedules. Shared-ride taxicabs may sacrifice a degree of directness to serve more than one origin-destination pair at the same time. Finally, taxicabs carry one or a few passengers. Vehicles that transport larger numbers of passengers are not taxicabs, as these operations more closely resemble commuter vans or minibuses and cannot offer service that is both direct and demand-responsive (as taxicabs do). Manila's jeepneys, for example, cruise city streets like taxicabs but gather as many concurrent passengers as possible (Thomson 1977).

Though many Americans encounter the taxicab in the form of the licensed "yellow taxi," much of the world does not. The Design Trust for Public Space (2007) writes, "In most cities...there is no distinction between 'taxis' and what (New York City) calls 'livery vehicles.' In such cities, taxis are the dominant term of usage and 'liveries' generally refers to unregulated or even illegal for-hire vehicles" (9). Ultimately, then, regulations and licenses legitimize and define the taxicab with a certainty that description cannot.

No singular, precise definition encompasses the global range of services that one can reasonably call taxicabs.

The taxicab is part of a broader transportation category known as paratransit—the spectrum of modes that lie between private cars and conventional mass transit (Cervero 1997).² Meyer et al. (1965) have noted that few services occupy the paratransit spectrum in most American cities aside from taxicabs, jitneys, and limousines. Nevertheless, the term comprises a broad range of flexible transportation types that rarely adhere to fixed routes or schedules and usually operate privately. Other common paratransit examples include airport shuttles, minibuses, and commuter vans (see Table II-1). Taxicabs charge higher fares than most other forms of paratransit but are also the most flexible in the “many-to-many” service they provide between almost any pair of origins and destinations within a city (Cervero 1997). Their flexibility and relative ubiquity in American cities gives taxicabs the potential to serve many origin-destination pairs more efficiently than buses can. Restrictions on market entry and other regulations constrain the paratransit industry as well as taxicabs in most U.S. cities, but taxicabs remain privately operated, unsubsidized, and unplanned, with the theoretical ability to serve any market but the practical need to earn a profit. One hypothesis that informs this thesis is that the conditions of operational freedom and regulatory restriction within which taxicabs operate encourages a suboptimal distribution of taxicab service in American cities like Boston. Attributing gaps in taxicab service to regulatory conditions

² Although Cervero himself does not classify exclusive-ride taxicabs as paratransit, Gilbert and Samuels (1982) and others do.

is difficult, however, when numerous other factors also influence the distribution of that service.

This thesis emphasizes the taxicab's role as a form of *public transportation*, a term with many uses that requires a precise definition here as well. Public transportation, as used throughout this thesis, refers to modes that are available to any passenger for a given fare and do not require full or partial ownership of the means of transportation itself. Privately-owned cars and bicycles are not public transportation; subways, public buses, ferries, and many (but not all) forms of paratransit, including the taxicab, are public transportation. The price of using public transportation may vary, but by the definition given here its price must not exclude the majority of potential passengers. Finally, public transportation need not be publicly owned, just publicly available. Throughout this thesis, the definition just provided will distinguish public transportation from mass transit, the latter of which will refer to fixed-route, fixed-schedule vehicular transportation that carries many passengers who board and alight at predetermined stops. Although this thesis closely examines the taxicab's *relationship* to mass transit, it considers the taxicab to *be* a form of public transportation that should complement mass transit in order to ensure a higher level of mobility throughout Boston or any other city.

Table II-1: Common forms of paratransit: the spectrum of modes between private cars and mass transit

		Service Types	Service Configuration	Typical Passenger Loads	Driver	Cost	Typical Regulatory Jurisdiction	Degree of Regulatory Restrictiveness
Private car		On demand (owned by user)	Many-to-many	1-4	Owner	High	State	Low
Commercial paratransit	Carsharing	On demand	Many-to-many	1-4	Subscriber	Moderate	City/state	Low to moderate
	Peer-to-peer carsharing	On demand	Many-to-many	1-4	Subscriber	Moderate	City/state	Low to moderate
	One-way carsharing	On demand	Many-to-many	1-4	Subscriber	Moderate	City/state	Low to moderate
	Exclusive-ride taxicab	On demand, phone & hail request	Many-to-many	1-4	For-hire	High	City	High
	Shared-ride taxicab	On demand, hail request	Many-to-many	3-4	For-hire	Moderate	City	High
	Dial-a-ride (specialized)	On demand, phone request	Many-to-many	6-10	For-hire	Low	City/state	Low
	Dial-a-ride (airport shuttle)	On demand, phone & hail request	Few-to-one	6-10	For-hire	Moderate	State	Low to moderate
	Jitney (circulator)	Regular route, fixed stops	Fixed-route/loop	6-15	For-hire	Low	City	Moderate to high
	Jitney (transit feeder)	Regular route, hail request	Many-to-one	6-15	For-hire	Low	City	Moderate to high
	Jitney (areawide)	Semi-regular route, hail request	Many-to-many	6-15	For-hire	Low	City	Moderate to high
Commuter vans	Pre-arranged, scheduled	Few-to-one	6-15	For-hire	Low	State	Low	
Mass transit		Regular route, fixed stops	Fixed-route	10 or more	For-hire	Low	Metropolitan area	High (publicly owned)

Source: Robert Cervero, *Paratransit in America* (1997, 15)

B. Historical development of the taxicab

TAXICAB ORIGINS

Developments during the twentieth century obscured the American taxicab's fundamental relationship to more conventional forms of public transportation, but a review of its history makes that relationship more comprehensible. The modern taxicab represents the culmination of an evolutionary process that began long before the automobile and mass transit existed. Jackson (1985) argues that no urban mass transit system existed before 1825, stating that "horse-drawn carriages for hire...represented the public mode for short trips"³ (33). Gilbert and Samuels (1982) offer the most comprehensive historical account of the taxicab's origins and development, also noting that the European horse-drawn carriage or hackney is the "earliest direct ancestor" of both taxicabs and mass transit (10). Hackneys first appeared in Paris and London during the early seventeenth century, cruising city streets freely in search of passengers, while some owners established stands where patrons could find available vehicles waiting.⁴

The hackney spread from Europe to America and prevailed as "the first public transportation used by the general public" until the 1800s, when its service began to

³ Jackson defines mass transit here as "operation along a fixed route, according to an established schedule, for a single fare" (33).

⁴ The cabriolet, a faster successor to the hackney that appeared in Paris around 1800, is another technological (and etymological) ancestor of the taxicab (Gilbert and Samuels 1982).

bifurcate into fixed-route transit on one hand and the taxicab on the other (Gilbert and Samuels 1982, 14). The French omnibus merged the hackney's function with the fixed-route operational mode of the stagecoach, and urban omnibus service boomed in the eastern United States beginning in the 1830s (Jackson 1985). While the omnibus represents the emergent thread of mass transit, nineteenth-century technological developments yielded sleeker variants of the hackney carriage; however, the twin inventions of the internal combustion engine and electric traction precipitated a more complete divergence of transit and paratransit by providing each with its optimal technology. As Gilbert and Samuels (1982) write, "the taxicab and the streetcar were about to be born" (24).

The modern taxicab's true origin, of course, follows the twentieth-century advent of the automobile. Several motorized cabs were developed in the United States and Europe during the final years of the nineteenth century. In 1907, Harry Allen introduced a fleet of 65 gasoline-powered automobiles to New York's streets and expanded this operation tenfold within a year, obtaining cab stands at the city's major hotels. Allen receives credit for coining the term "taxicab," having named his company the New York Taxicab Association (Gilbert and Samuels 1982). Automobile taxicabs rapidly rendered their horse-drawn predecessors obsolete.

In the decades leading up to the Great Depression, the growing taxicab industry's dominance by individual owner-operators and small firms gave way to larger-scale fleets. John Hertz's Yellow Cab Company in Chicago became the world's largest taxicab company by 1925 with a fleet of 2,700 vehicles. Several firms extended their operations to multiple cities, and some also began manufacturing their own taxicabs. Fares dropped significantly during this period, making taxicab service available to less

affluent riders, while innovations like telephone dispatching also developed.⁵ During the 1910s and 1920s, the familiar “yellow taxi” emerged as the American taxicab acquired many of its present-day characteristics (Gilbert and Samuels 1982).

THE GREAT DEPRESSION AND INDUSTRY REGULATION

Regulation has heavily influenced the taxicab’s evolution in the United States. Unlike mass transit, however, taxicabs have continued to operate privately. The taxicab and electric streetcar, on separate trajectories since their nineteenth-century origins, each underwent pivotal regulatory transitions during the Great Depression. Teal and Berglund (1987) write, “In most cities, the taxicab industry was brought under municipal or state regulation during the late 1920s and 1930s, largely because of the extremely competitive conditions stimulated by the Depression” (37). Other urban transportation modes also faced these circumstances: The streetcar was “unchallenged as an urban transportation carrier” before World War I, but wartime inflation caused bankruptcy for one third of streetcar companies (Gilbert and Samuels 1982, 62). The jitney, a privately-operated automobile similar to the taxicab that drove along streetcar routes and picked up waiting passengers, grew rapidly along with taxicabs but encountered well-organized opposition in the streetcar companies from whom they diverted passengers. The streetcar industry pushed for municipal anti-jitney regulations, including restrictions on ridesharing, that helped to eliminate the majority of jitneys by 1920. Nonetheless,

⁵ After entering the taxicab business in 1907, Hertz reduced his company’s mileage rates from the prevailing \$0.40 to \$0.20 and eliminated charges for deadhead travel to pickup points (Gilbert and Samuels 1982).

private automobiles continued eating into transit ridership, and the onset of the Depression accelerated the mode's decline: Streetcar ridership dropped by 30 percent from 1930 to 1935 and another 20 percent in the next five years, while the Public Utilities Holding Act of 1935 forced most electric power utilities to divest themselves of their streetcar assets. With some exceptions, American transit's decline in profitability never recovered, and by 1975, 90 percent of transit ridership occurred on systems that had transitioned to public ownership (Gilbert and Samuels 1982).

The Depression imposed economic hardship on both the taxicab and mass transit industries, but its effects on each produced two distinctly different outcomes. While the decline of transit accelerated during that period, the taxicab emerged as a heavily-regulated but still private—and profitable—mode of urban transportation. Before the Depression, taxicabs did not operate entirely free of regulation, but the ordinances that did exist only imposed minor requirements such as posting rates of fare.⁶ Municipal regulations that came about in the 1920s served to protect passengers by requiring insurance and limiting fare rates. A few instances of taxicab “wars,” furthermore, had demonstrated the negative aspects of competition by forcing rapid fare reductions and encouraging a variety of illegal behaviors (Gilbert and Samuels 1982).

When the Depression struck, the ease of entry into the taxicab industry and high unemployment in other industries precipitated a glut of taxicab drivers. Gilbert and

⁶ Boston had established its Hackney Carriage Unit along with its police department in 1854, well before the automobile even existed.

Samuels (1982) write, “The expansion of the supply of taxi service at a time of economic depression meant that more taxis competed for fewer passengers. Rate wars flared in cities throughout the country” (67). The chaotic competition that resulted had negative impacts on legitimate taxicab operators and on cities themselves. Consensus thus emerged among public officials and established taxicab operators that regulation was necessary. In 1930 the Massachusetts legislature limited Boston’s total taxicab industry to 1,525 vehicles and within a few years similar ceilings had appeared in New York, Chicago, and other major cities. Fixed fare rates and mandatory taximeters also became commonplace during this time, as did standards for vehicle conditions and insurance. While these changes left taxicabs in private hands, they transformed the industry into a public utility in most cities and further encouraged the development of large fleets. The taxicab’s role also shifted: “The taximeter requirement made the taxi operators providers of an exclusive-ride service. Unable to provide shared-ride service, taxis could no longer compete with mass transit modes” (Gilbert and Samuels 1982, 73). In general, however, Gilbert and Samuels (1982) contend that taxicab operators and passengers largely benefited from the new degree of regulation. Koehler (2004), however, argues that the objective of taxicab regulation shifted from consumer protection to income protection during the 1930s. Most of the policies that large American cities enacted during that decade persist in those same cities today, although some have since deregulated their taxicab systems.

C. The taxicab’s role in urban transportation

The taxicab’s history demonstrates that its function as urban transportation fluctuates. Changing technological, economic, and regulatory conditions have precipitated significant adjustments in how taxicabs serve cities. The literature on taxicabs reveals a wide array of perspectives concerning the taxicab’s actual and ideal roles in urban

environments, as well as recommendations for realizing the ideal. *Taxi 07: Roads Forward*, by the Design Trust for Public Space and the New York City Taxi & Limousine Commission (2007), offers one broadly-scoped example, posing the following questions:

“How can the taxi best function as a vital part of New York’s public realm? And how can the taxi system be optimally regulated to provide an excellent transportation service for all of its passengers and stakeholders—and for the city at large?” (8)

While the literature does contain instances of such comprehensive visions, it more commonly defines a narrower set of stakeholders such as taxicab passengers or operators (drivers and owners). Taxicab regulations are frequent subjects of this literature, presented as key mechanisms by which to achieve specific objectives for the industry.

Literature that addresses the taxicab’s role in urban transportation tends to occupy one of three tiers corresponding to its breadth of inquiry: At the highest tier, studies situate the taxicab within the complete multimodal transportation system and consider how the taxicab system can best fit the city it serves. The second tier of literature treats the urban context and other transportation modes as exogenous, evaluating the taxicab industry in terms of social efficiency but confining its scope to that mode alone. The third tier, finally, focuses attention on one taxicab stakeholder group—most frequently taxicab operators—and examines how that group might better achieve its own goals, such as operating more profitably. Each tier’s literature reflects a variety of attitudes toward the purpose of the taxicab industry and offers different answers to the following question: To what extent and in which situations, if any, should the taxicab industry’s goals as a

private enterprise become subordinate to the industry's purpose as a public transportation resource and a provider of urban mobility?

TIER ONE: THE TAXICAB WITHIN THE URBAN CONTEXT

The first tier of literature considers the taxicab as part of a larger urban transportation system, typically emphasizing the taxicab's optimal role within that system and within cities. Frankena and Pautler (1984) observe that the taxicab provides a substantial portion of public transportation services in cities. In a comprehensive historical review of the taxicab industry, Gilbert and Samuels (1982) describe an "integrated paratransit-transit dream" in which "a variety of flexible services...would supplement fixed-route services" (4). Like Alexander et al. (1977), they cite conventional transit's inability to provide satisfactory mobility to certain urban areas in a cost-effective manner, and see taxicabs as one solution to that problem. Their book's historical account examines the taxicab's role through this lens, supporting the argument that public transit programs and subsidies should incorporate taxicabs. Webster et al. (1974) advance a similar argument, emphasizing "improvement in intra-city public transportation within urbanized areas through better integration of taxi services with mass transit" (6-3). They cite key operational advantages of the taxicab as a mode, including its low capital requirements and its ability to serve a wide range of origin-destination pairs.

Cervero (1997) advances a similar case for paratransit in general. Paratransit, he states, can encourage modal shifts away from cars, increase travel choices, enhance mobility in poor neighborhoods, and shoulder a portion of the costly peak demand that mass transit systems handle. Cervero's definition of paratransit excludes conventional taxicab service but he devotes a chapter to shared-ride taxicab service, writing, "In the hierarchy of paratransit service coverage, shared-ride taxis, with their potential to

provide many-to-many services, stand at the very top” (31). Trips between airports and downtown areas are the largest market niche for taxicab ridesharing, but Cervero offers a Berkeley case study in which unsubsidized shared-ride taxicabs effectively extended existing bus service between a transit station and a racetrack four miles away. More than 60 percent of rail passengers transferred to taxicabs to reach the racetrack and the taxicab operators matched the competing bus route’s \$2 fares. In a similar study, Teal et al. (1979) describe the taxicab’s entry into formal transit provision during the 1970s. In that decade, taxicab firms created contractual arrangements with public agencies to provide subsidized demand-responsive transit services in California and other parts of the United States.

Despite the potential these examples demonstrate, such cases are rare, and others have blamed excessive regulations in American cities for the dearth of urban transportation options between the extremes that the private automobile and fixed-route transit represent (Meyer et al. 1965). American taxicab service, furthermore, is often too expensive to function as useful public transportation for many socioeconomic groups. Gilbert and Samuels as well as Cervero argue for extending the public subsidies, incentives, and regulations that benefit mass transit to the taxicab and paratransit industries, facilitating less distorted competition between the modes, integrating their service, and better matching each mode with its proper market.

Recent literature has further supported integrating taxicabs within the larger urban system, often adopting a pragmatic approach. The Design Trust for Public Space (2007) studies the New York City taxicab system from the widest possible angle, exploring the system’s functions as an urban symbol and as an extension of public space. Rather than prioritizing one perspective, the study enumerates three primary stakeholder

groups—passengers, drivers, and owners—and seeks to balance the needs of each in the objectives it develops.⁷ Those objectives include efficiently matching taxicab supply with demand and providing economic value to all three stakeholder groups. The study’s “Guiding Principles” yield recommendations such as lower ridesharing fares, peak-period surcharges, new medallion rules, and additional taxicab stands. The study also notes, “Taxis and transit should be seen as natural complements, part of a comprehensive package of alternatives that can compete with the private car” (132). To this end, it recommends a closer working relationship between the relevant agencies and suggests replacing low-volume bus routes with taxicabs. Historical and recent evidence therefore suggests that a symbiotic relationship between taxicabs and mass transit is feasible and desirable, but this evidence also points to a variety of obstacles that have impaired such a relationship.

TIER TWO: THE TAXICAB AS AN INDUSTRY

The second tier of taxicab literature focuses more narrowly on the taxicab industry, studying demand for the mode and inquiring how taxicabs might increase their benefits to passengers or society (including drivers and owners). Unlike the previous category, these studies examine taxicabs as a self-contained system and largely place the urban context beyond their analytic scope. Net social benefit, as conceived by much of this literature, is the sum of aggregate consumer surplus and profit, the latter of which is

⁷ The study’s list of major stakeholder groups omits urban residents who do not use taxicabs, despite the taxicab’s direct and indirect impacts on these individuals.

often assumed to be zero under perfect competition. By invoking the idea of a social optimum, this tier differs from the first in a critical way: Here, the literature assesses the taxicab industry's contribution to social welfare independently of its relationship to other transportation modes. The highest level of taxicab service for a given fare rate and supply cost is assumed to be the best possible outcome, regardless of whether mass transit or another mode could provide that service more efficiently, and regardless of the taxicabs' less quantifiable impacts on the city. In short, this tier's literature tends to simplify the problems addressed in the first tier.

Many have studied the taxicab industry's fare controls and entry restrictions in order to understand how each mechanism affects the equilibrium of taxicab supply and demand in various cities (Douglas 1972; Schroeter 1983; Koehler 2004; Schaller 2007).

Critiques have cited negative impacts on potential or actual passengers, especially in the form of lower service levels, as the principal drawbacks of those regulations (Frankena and Pautler 1984). Teal and Berglund (1987) assess cases of taxicab industry deregulation according to their effects on prices, levels of service, productivity, and innovation, leaving aside questions of how taxicabs complement other urban transportation modes. Others contend that properly informed regulations can contribute to socially optimal or second-best outcomes but acknowledge the difficulty of obtaining "suitable information" (Beesley and Glaister 1983, 594; Cairns and Liston-Heyes 1996).

Some economic literature has modeled taxicab service quality as a function of pricing, noting that fare regulations can be used to reduce average passenger waiting times, increase taxicab utilization, and achieve an outcome that maximizes social benefits (Douglas 1972; Arnott 1996). Yang et al. (2002) develop a network equilibrium model for taxicab movement and passenger demand, using the market's spatial structure and

other variables to identify a fare rate and fleet size that would yield the socially optimal outcome in Hong Kong. Matsushima and Kobayashi (2010) conceive of the urban taxicab market as spatially disaggregate, developing a theoretical model of the interaction between supply and demand in localized “spot markets.” They recognize that both passengers and drivers must make imperfect guesses about the condition of a given spot market which informs their decisions to visit that location.

In general, this literature reflects a belief that the taxicab industry should maximize its efficiency for a given fare price—a critical question, but one that addresses taxicab supply and demand in place of overall mobility. The simplified outlook evident in these studies reflects similar goals to those of the first tier—an outcome that benefits multiple stakeholder groups—but the two tiers differ in how broadly they define those benefits, and by which variables remain beyond their scope.

TIER THREE: TAXICAB STAKEHOLDERS

The third tier of taxicab literature focuses its analysis on separate stakeholder groups within the taxicab industry—typically operators or passengers—and those groups’ specific aims. For drivers, studies have sought more profitable or efficient modes of operation. For customers, literature has addressed finding a taxicab quickly. Recent technological developments have yielded data that enable more sophisticated approaches to these matters. Several studies have introduced models that predict the spatial distributions and route choices of taxicabs using GPS data on drivers’ past behavior, noting these models’ capacities to streamline radio dispatching and provide “context-sensitive route recommendations” to drivers (Ziebart et al. 2008, 1; Chang et al. 2010; Phithakkitnukoon et al. 2010). The same models could also offer potential customers the ability to quickly locate vacant taxis. Liu et al. (2009) use data on

Shenzhen taxicab drivers' routes and revenue to evaluate their "mobility intelligence," or income-maximizing skill. Another study proposes a system that optimizes and dynamically adjusts taxicab fleets' routes as they cruise for passengers, recognizing that drivers' individual decisions produce a "locally excessive supplement of taxis" that leads to detrimental competition for certain passenger clusters (Yamamoto et al. 2008, 560). This body of research seeks specific tools, often technologically-focused, that allow taxicab drivers to operate more efficiently and enable customers to travel more conveniently.

THE ROLE OF THE TAXICAB: PRIVATE ENTERPRISE OR PUBLIC TRANSPORTATION?

The literature indicates that taxicabs function as both public transportation and private enterprise in different situations. Webster et al. (1974) write that "taxicab companies and operators are the epitome of private enterprise" while mass transit "has become a public sector dominated industry" (v). American taxicab regulations emerged during the Depression with the primary goal of protecting the industry's profitability rather than ensuring the provision of a valuable public service. In Boston and in many other cities, those regulations remain in effect today. Some rules, like the requirement that a taxicab transport a passenger to any requested destination within its service area, do exist for the benefit of passengers. Mass transit systems often operate according to service standards that ensure minimum levels of mobility throughout a city, but no such standards (or subsidies) dictate the spatial distribution of privately-operated taxicab service. Thus, profitability exerts a more powerful influence on taxicab distribution than on the service of other public transportation modes.

Literature within the second and third tiers defined above suggests that economic conditions discourage the even distribution of taxicab service with respect to demand, confirming the existence of conflict between the mode's roles as a private industry and public transportation. Achieving socially optimal or "first best" levels of service has generally been considered an "unattainable ideal" (Arnott 1996, 318). Regulations that might yield results closer to the optimum usually require information that few public agencies have. Furthermore, the complexity of taxicab operations and the limited information available can even prevent individual firms and drivers from meeting demand in the most efficient or profitable way. In general, the constraint that taxicab operators must operate profitable service limits their ability to function as a pure form of public transportation.

Other characteristics of taxicab operations and travel demand, however, suggest a public transportation role for the mode that could become even stronger (and has been, historically). Many have pointed out that the taxicab *is* public transportation (Webster et al. 1974; Gilbert and Samuels 1982; Frankena and Pautler 1984). In cities where substantial cruising taxicab markets exist, including Boston, taxicab operations resemble transit even more closely; however, the spectrum of modes that lie between the exclusive-ride taxicab and fixed-route bus transit (as shown in Table II-1 above), along with the corresponding spectrum of fare rates, remains quite unpopulated in most U.S. cities. Finally, there are few cases of taxicabs formally complementing a public transit system, like the Berkeley example that Cervero (1997) describes, but these instances do occur, and some taxicabs also deliver demand-responsive transit under contract to public agencies (Teal et al. 1979).

When taxicabs do not have a formal relationship to a city's public transit system—the more common scenario—they still function as public transportation, and demand for cruising taxicabs overlaps with demand for mass transit and other modes. In cities with high levels of transit service, such as Boston, the market for taxicabs becomes more complex. How passengers use taxicabs when other modes are available, and when they are not, is a key question that this thesis addresses. The next section will prepare to answer that question with a more detailed discussion of who taxicabs actually serve, and how.

D. Groups served by taxicabs

One cannot understand the taxicab's role in any city without understanding *whom* the taxicab serves, and recommendations for improving a city's taxicab system should reflect an assessment of who will benefit from those improvements. What this thesis calls realized demand—taxicab pickups, drop-offs, and the passenger trips that occur between those two points—is a product of supply as well as demand. While supply is a spatial phenomenon, as the relative costs and availability of different transportation modes vary by location, the sources of demand are the individuals who desire transportation services. The spatial availability of taxicabs influences who benefits from them, but so does the nature of urban travel demand.

Two particular taxicab customer groups, as described in transportation demand literature, are of interest here: choice riders and captive riders. Beimborn et al. (2003) define each group as follows for mass transit, although the terms can apply to any mode:

“Choice users...have a realistic transit option available that connects their origin and destination at a time that meets their needs and works within the constraints of their household and life situation. Choice of transit occurs when travelers feel that the transit option is superior to other choices in terms of time, cost, convenience and comfort. In contrast, captive transit users might be bound to public transportation because of age, disability, income or family circumstances.” (2)

The taxicab, unlike transit, is easily perceived as a mode that mainly serves choice riders due to its high cost. Frankena and Pautler (1984), though, find evidence that lower-income people spend more money per capita on taxicabs than high-income individuals. Furthermore, transit service is poor in many urban areas. A 1978 study of Boston’s taxicab system found that its taxicabs largely provided “a very exclusive and unique service either for those with no other alternative or those who are willing to pay” (Mayor’s Office of Transportation 1978, 3). In light of the taxicab’s previously discussed role as public transportation, the choice between taxicabs and mass transit in cities like Boston, which have both, assumes particular relevance: Taxicab trips that complement mass transit or substitute for it should, logically, correspond somewhat (though not perfectly) to the presence of captive and choice taxicab riders.

Recent passenger surveys in New York City offer limited insight into taxicab demand and the reasons people use the mode. Most recently, a 2011 survey of nearly 23,000 taxicab passengers by the New York City Taxicab and Limousine Commission revealed basic demographic characteristics of New York taxicab riders (New York City Taxicab and Limousine Commission 2011). The summary of that survey’s results indicates the following:

- 65 percent are male.
- 42 percent earn at least \$75,000 per year, while only 7 percent earn less than \$25,000 (and another 19 percent chose not to give this information).
- 43 percent live in households with no cars.
- 54 percent are aged 35 or younger.

This evidence suggests that, in New York, the taxicab serves the relatively affluent and young but also smaller shares of poorer or older riders. Car owners and the carless both account for significant shares of taxicab usage. Also of interest were the following ridership characteristics:

- 25 percent of passengers use taxicabs daily, and an additional 41 percent use them weekly.
- Only 12 percent of passengers rate the experience of riding a New York City taxicab as poor or below average.

This evidence demonstrates that New York taxicabs most likely serve a smaller proportion of captive riders than choice riders, who place high values on their time and comfort. New York's (and especially Manhattan's) good transit service lends additional support to this hypothesis. Schaller Consulting (2006) finds that 71 percent of New York City taxicab trips transport residents of Manhattan, the borough where transit service levels are also highest and transit is more likely to be an option for taxicab passengers.

MODE CHOICE AND DEMAND MODELS

Mode choice plays an important role in distinguishing choice taxicab riders from captive riders. The taxicab, as one urban transportation mode among many, provides a service for which several substitutes typically exist in cities. The availability of most modes,

including taxicabs, is unevenly distributed throughout a city, so a specific set of individual preferences will have different mode choice outcomes in different locations. That same spatial variation can also result in no trip occurring, if the minimum costs associated with any available mode (including waiting times or travel times) are higher than an individual's willingness to pay for a given trip. Regardless of whether choice riders and captive riders value the taxicab differently, the two groups are distinguished by the range of modes available to each. An individual who does not value time highly might ride the bus when a bus route is nearby but hail a taxicab late at night when that bus route no longer runs. The subjective preferences are the same in both cases; however, the individual is a choice rider in the first instance and a captive rider in the second, and the outcome changes.

Disaggregate discrete choice models are one means by which these aspects of travel behavior are studied. These models represent behavior as nominal choices from a given set of available transportation modes, and embody the assumption that the mode one ultimately selects maximizes his utility. More specifically, logit models such as binary logit (in which passengers choose between two options) and multinomial logit (in which passengers choose from a set of more than two options) reflect an underlying theory of mode choice that helps to illustrate different types of taxicab demand.

Within the logit framework, a trip-maker selects the mode that maximizes his utility (Small and Winston 1999). Utility is a function of modal attributes, characteristics of the trip-maker, and a random component that reflects unobserved factors influencing the choice; the mode with the highest utility has the highest probability of being chosen in a particular instance. In this thesis, a realized taxicab trip indicates the taxicab's higher random utility in comparison with other available options. For some taxicab

passengers—choice riders—the taxicab’s utility will exceed that of several other available modes. For captive riders, it will surpass a more limited set of choices, and these individuals would possibly choose a different mode if it were available. In this framework, unavailability is occasionally equivalent to extremely low utility caused by excessive time or monetary costs.

Logit models can easily misrepresent the mechanics of mode choice, though, by oversimplifying the decision process. In many cases, the nested logit model more accurately represents the multiple components of travel decisions: “In most transportation settings, mode choices are made jointly with other travel-related decisions. For example, a commuter may simultaneously choose what mode to use and how many cars to own...If the two choices depend on one another, it is an error to pretend that one is exogenous while analyzing the other” (Small and Winston 1999, 21). Nested logit models divide joint choices into groups of potential outcomes, where a decision tree represents the conditionality of joint choices and the correlations among those outcomes. In this thesis, decisions like where to live and whether to own a car are not necessarily unrelated to particular mode choices. The nesting structure of this type of logit model reflects the relationships between these sets of choices.

For this study of taxicabs, an important consideration is the set of potential taxicab passengers who do not make taxicab trips because of the mode’s relative unavailability. As mentioned above, we can understand unavailability as very low utility: If taxicabs are too expensive or require a long wait before one can obtain service at a certain location then a potential passenger might choose a higher-utility mode, as personal preferences dictate, but the person might also choose to forgo that trip altogether if no reasonable substitute exists. Using the nested structure just described, the relative utility of not

traveling in comparison to traveling determines whether the trip will actually happen, and the inconvenience or discomfort of making that trip influences the choice. The modes available to the individual for a particular trip have a significant impact on that inconvenience and thus affect the relative utilities of traveling and not traveling.

TAXICAB DEMAND AND WILLINGNESS TO PAY

Logit models potentially reflect how subjective preferences as well as objective conditions influence transportation demand. Relative utility drives mode choice as well as whether a trip happens in the first place, and one's willingness to pay for travel is another manifestation of that decision process. If the time and monetary costs of travel are important factors influencing a trip's utility (or disutility), fluctuations in either will be expected to impact mode choice as well as the decision to travel. When these fluctuations occur, riders who are captive to one mode are likely to respond differently than riders with choices, as increasing disutility pushes the latter toward another mode while discouraging the former from traveling at all. In the taxicab's case, captive riders (who lack a car or mass transit access) will become less likely than choice riders to travel at all in situations where taxicab service is poor, and will consequently suffer a greater loss of mobility.

In practice, this situation occurs in radio-dispatched taxicab markets, which exist "in most cities, including many without public transit, and (are) used heavily by lower income people who do not own cars" (Frankena and Pautler 1984, 12). Dispatched taxicabs require longer waits than cruising taxicabs and likely benefit from captive rider markets where they face less competition from comparable modes. In these markets, realized demand reflects customers' willingness to pay in the form of higher time costs as well as the fare itself. Frankena and Pautler also observe that cruising taxicab

markets primarily exist in downtown areas of large cities, where mass transit is usually best and choice riders therefore predominate.

Douglas (1972) describes another valuable model for urban taxicab markets that illustrates basic dynamics of taxicab demand and willingness to pay. Because potential taxicab customers cannot signal to drivers a willingness to pay extra for a reduced wait, they must accept a stochastic wait before finding the next available taxicab. In other words, the randomness of the cruising taxicab market precludes taxicab quality differentiation in the Douglas model. In reality, some quality differentiation is possible: Douglas notes that taxicabs may congregate at hotel taxicab stands where higher tips are expected, so these customers are informally signaling a willingness to pay for better service. Conversely, known concentrations of passengers with lower willingness to pay may attract fewer taxicabs and receive poorer service. In both examples, taxicab drivers' perceptions of demand in specific locations influence their decisions to cruise for passengers there.

Douglas explains that different combinations of taxicab fares and service levels are preferred by passengers who value time differently. The Douglas model treats demand as a function of two variables: trip price and service quality, or expected delay. The spatial density and speed of *vacant* taxicabs (not total taxicabs) determines expected delay in the model, assuming random movement of vacant taxicabs, but demand directly relates to the vacancy ratio: An upward price shift decreases passenger demand, which in turn raises the ratio of vacant taxicabs, improving service quality and reclaiming some of that lost demand. Thus, price exerts two opposing effects on taxicab demand. In the model, a single fare rate for all taxicabs will produce a market equilibrium with an evenly-distributed service quality. Douglas writes, "The existence of

two or more groups with different time values creates a conflict situation” (125). Any equilibrium in which every customer faces a given price and expected delay will favor some customers over others, depending upon the degree to which some would pay more or less to incur a longer or shorter wait.

CONCLUSIONS

Because vacant taxicabs, expected delays, and potential customers are not evenly distributed, as the Douglas model necessarily assumes, different urban locations have different levels of taxicab service as well as demand. Fare rates, however, are constant and regulated in Boston and in many other cities. The preceding discussion yields two important conclusions about taxicab demand:

1. Choice riders and captive riders respond differently to variable taxicab service levels, which constitute the primary form of quality differentiation in a fare-regulated taxicab market. Captive riders are more likely to wait longer for a taxicab or forgo a trip altogether, since they lack alternatives by definition.
2. Some taxicab customers may be willing to pay a higher fare in exchange for a shorter wait, while others may prefer a longer wait in exchange for a lower fare, depending upon how each values time. The nature of taxicab markets limits the ability to make either tradeoff, but Douglas suggests that tipping is one mechanism by which it can occur.

The question thus arises of how urban taxicab service levels vary spatially. Do captive riders receive poorer service while choice riders and customers willing to pay more get better service? If so, is that a socially desirable situation? Finally, how does the interaction of the taxicab system with mass transit influence realized taxicab demand?

These questions all relate to the central inquiry of this thesis: To what degree does the taxicab act as a substitute or complement to mass transit? A brief return to that question concludes this chapter.

E. The taxicab as transit complement and substitute

The preceding discussion of taxicab demand and its relationship to service levels, along with my review of literature that argues in favor of the taxicab's role as public transportation, must accompany a closer examination of the taxicab's role in a city like Boston, where both mass transit and cruising taxicabs are widespread. The concepts of captive and choice riders, introduced above, provide a useful starting point. If the taxicab is operationally suited to provide service where fixed-route transit does not, and if "taxis and transit should be seen as natural complements" (Design Trust for Public Space 2007, 132), then captive taxicab riders, who find themselves temporarily or permanently without access to fixed-route transit, stand to gain the most mobility from that complementary relationship.

The truly captive taxicab rider, of course, does not lack mass transit access alone. A variety of other modes serve even the urban areas where mobility is lowest, and the most ubiquitous of these modes is walking. For reasons which Chapter Four will address in greater depth, other common modes are less relevant to the research objectives of this thesis, as various characteristics make them less likely substitutes for taxicabs or mass transit: The private automobile is differentiated by the requirement of ownership and the constraints imposed by parking. Bicycle travel is limited by age, physical ability, weather conditions, and other factors that significantly curtail the population that can rely upon it. Finally, door-to-door paratransit services like Boston's THE RIDE, which the Massachusetts Bay Transportation Authority (MBTA) operates,

closely resemble taxicab and mass transit, but only for the disabled individuals eligible to use their services. While neither mass transit nor taxicabs are universally accessible to the disabled, they are available to a wider range of users than private automobiles or bicycles. The most widely available and “public” modes—taxicabs, mass transit, and walking—are therefore the focus of this research.

The taxicab’s primary function as a complement to mass transit is the mobility it offers its captive riders, as I have just defined them, and that complementary role has both spatial and temporal components: Mass transit service is not only uneven in its spatial distribution throughout a city, but also in its distribution by time of day. In Boston’s case, no transit is available whatsoever during a certain period of the night and the taxicab’s captive market share increases accordingly during that time (although overall travel demand decreases). Furthermore, one’s location at an origin near a transit station or bus stop does not constitute transit access if transit does not also serve the desired destination. For these reasons and others, an individual’s status as a captive taxicab rider is circumstantial, and one who normally enjoys a choice might frequently demand travel in situations where taxicabs are the only option. Many others who live in locations with poor transit access will find themselves captive riders on a more regular basis. The effectiveness with which taxicabs serve these captive riders, by filling in the gaps that transit does not reach, is the central question of this thesis.

Choice taxicab riders, in contrast to captive riders, use the taxicab in its role as a transit substitute. While this group depends less upon the taxicab, in the sense that mass transit is available for their desired trips, the taxicab’s substitute role is nonetheless important. The ability to pay a higher fare and receive faster, safer, and more comfortable transportation is a clear benefit to those who find the tradeoff worthwhile.

Like captive riders, choice riders also exist circumstantially, and an individual will potentially play both roles at various times.

The coexistence of captive and choice taxicab markets in many cities dictates two separate roles for the industry. Both roles have undeniable merit, and both provide clear benefits to groups that occasionally overlap, as this chapter has shown; however, evidence suggests that the taxicab industry will not serve both in the same way. The literature indicates uncertainty about the optimal spatial allocation of urban taxicab supply, or the feasibility of achieving any defined optimum, but a concern for social equity affirms the value of ensuring a basic level of taxicab service for the mode's captive riders. Obtaining detailed insight into how a city's taxicab system serves each market, and learning whether one receives priority over the other, will yield valuable insight into whom the taxicab truly serves and whom it can and should serve better. This thesis investigates that question for Boston's taxicab industry, and the next chapter introduces the Boston case for analysis.

III. THE BOSTON CASE

This chapter builds upon the foundation laid in Chapter Two by introducing a specific city, Boston, and its taxicab industry. The characteristics of Boston and the transportation modes that serve the city make it an ideal case study by which to understand general principles of the taxicab industry in the United States, as discussed in the previous chapter. A summary of these conditions begins this chapter, followed by a more detailed description of Boston's taxicab industry and the regulations that shape it. The chapter concludes by restating the research objectives of this thesis.

A. Transportation patterns in Boston

The American taxicab as we know it today emerged in major cities like Boston, New York, and Chicago during the early twentieth century because those dense urban centers favored the types of mobility that taxicabs provide; however, as mentioned in the previous chapter, the taxicab operates in a wide variety of urban and suburban environments because it can economically serve origin-destination pairs that have less concentrated demand in addition to serving the vibrant downtown areas where it is most visible. A brief description of the transportation context within which Boston's taxicabs operate is a necessary background to the subsequent discussion of the taxicab's role in Boston's multimodal transportation system.

A variety of conditions influence the taxicab's role in Boston and its metropolitan area. Boston's urban form and its transportation system resemble those of other large cities like Chicago and San Francisco, exhibiting qualities that are relatively uncommon in the American urban environment (Thomson 1977). Boston is one of America's oldest major

cities, with a dense core surrounded by newer, lower-density, and largely automobile-dependent suburbs. Thomson (1977) has characterized Boston as a city that exemplifies a “weak-centre” transportation strategy, which possesses

“a radial road network serving a small city centre to which a relatively high proportion of city-centre workers travel by car...A city centre of the magnitude implied, even though relatively weak, requires considerably more employment than can normally be transported by private automobile.” (130)

The situation Thomson describes has interesting implications for the taxicab in a city like Boston. The type of transportation demand to which he refers—commuters traveling between their homes on the metropolitan periphery and their jobs in the city center—requires that public transportation serve the central city. Indeed, transporting commuters to and from central Boston during peak periods is the most important function of the city’s principal public transportation system, the MBTA, although it is certainly not that system’s only purpose. Peak period commuter travel, however, is perhaps the transportation market in which taxicabs are least competitive with fixed-route mass transit, as transit service tends to be highest at times and in places where demand is most concentrated. The taxicab’s greatest advantage, relative to transit, emerges when demand is spread more thinly among a variety of origin-destination pairs.

In its 1978 *Boston Taxi Study Final Report*, the Mayor’s Office of Transportation describes Boston as a “good taxi town” for a variety of reasons: compact entertainment and commercial districts; dense, centrally-located residential neighborhoods; an airport relatively close to its downtown; and “street patterns and limited parking (that) discourage wholesale use of the private auto for point to point trips in the downtown area” (4). In opposition to these favorable conditions, the study cites increased

automobile use in central cities and the suburbanization of population as widespread reasons for declining taxicab demand throughout the United States. The competing forces that strengthen or weaken taxicab demand in a city like Boston fit well with Thomson's "weak-centre" characterization of the city and its transportation.

Figure III-1: Map of Boston and MBTA rail lines



Boston's urban structure, its transportation patterns, and especially the prevalence of modes other than the private automobile within the city support the taxicab's role as an important component of its transportation system. The *Boston Transportation Fact Book and Neighborhood Profiles*, written by the City of Boston and most recently published in 2002, provides detailed information about the city's transportation patterns. The document highlights several general patterns that influence the city's modal split and support Thomson's "weak-centre" model of Boston. The following have particular relevance for this thesis:

- **General travel patterns:** 25 percent of all trips starting in Boston proper begin and end within the same neighborhood, and an additional 19 percent begin or end in the central part of the city. About half of all trips to or from Boston's core both begin and end there.⁸ Mass transit's mode share is highest for these core trips (40 percent) while the mode share for walking is highest for intra-neighborhood trips (74 percent).
- **Mass transit:** Transit is a viable transportation option for much of Boston's population. The city's subway system is the oldest in the United States, and the MBTA carries the fourth-highest ridership of any transit system in the nation. As of 2002, 57 percent of Boston's population and 79 percent of its jobs were within approximately a 10-minute walk of a mass transit or commuter rail station (City of

⁸ The study refers to the following as Boston's "Core" neighborhoods: Downtown, North End/West End, Chinatown/Theater District, and Back Bay/Beacon Hill (City of Boston 2002).

Boston 2002, 2). Of the 283,000 daily trips into Boston's core neighborhoods from suburban origins, nearly half used public transportation, and the City notes, "Few cities in the U.S. are as fortunate as Boston in this regard."

- **Walking:** Walking accounts for a significant mode share in Boston. Three of every ten trips in Boston occurred on foot as of 2002. This share could be even higher in reality, as much urban walking activity covers distances that are too short to count as "trips" in most transportation studies.
- **Taxicabs:** Using the 2002 estimate that roughly 2.7 million trips terminate in Boston on a daily basis, the taxicab's mode share in the city is between 1 and 2 percent, and possibly greater.⁹
- **Private automobile:** As in virtually all American cities, the private automobile plays a major role in Boston. More than half of trips to or from Boston's core neighborhoods are made by car, with a much higher automobile mode share for trips that begin or end in less central parts of Boston. The car's role has grown recently, too: Boston's increasing desirability to higher-income residents caused automobile registrations within the city to grow by 36 percent from 1990 to 2001, although the city's population only grew by 3 percent during that same period. Parking, however, places an important limit on car transportation, as Boston's

⁹ This estimate is based upon taxicab trip totals from the 2010 and 2011 data used throughout this thesis, and the knowledge that every taxicab trip represents at least one passenger trip but possibly more. The estimate requires the additional assumption that Boston's total trips have not changed substantially during the past nine years.

parking supply “is constrained by statute, geography, and urban fabric, and has grown much more slowly than parking demand” (City of Boston 2002, 10).

These patterns indicate critical present and future roles for the taxicab in Boston. While transit and walking enjoy larger mode shares than in most American cities, recent evidence indicates the growing presence of the automobile in Boston (and a higher automobile mode share where traffic and parking do not constrain its use). Non-automobile modes prove quite effective at transporting passengers to and from Boston’s center, while walking satisfies the majority of short-distance trips; however, these modes are less competitive with the car for most other types of trips. The taxicab’s ability to efficiently serve travel demand that few modes other than the car are able to serve, as described in Chapter Two, gives it a valuable niche in Boston’s transportation system as a complement to transit and walking. Furthermore, the increased presence of affluent car owners in Boston suggests an additional role for the taxicab as a transit substitute: Residents (or tourists) who might never consider transit, even for trips that transit serves well, will potentially make those trips by private car, but the taxicab can present those individuals with a desirable alternative mode of travel that encourages them not to drive themselves. There are many benefits associated with reducing car travel by shifting trips to other modes, including reductions in vehicle emissions and traffic congestion.

B. The Boston taxicab industry and regulatory context

Boston’s large taxicab system is one of many municipal taxicab systems in its metropolitan area. Substantial regulation shapes this system and its operation, and the City of Boston bears responsibility for “protecting the public’s interest in providing safe, efficient cab service at a reasonable cost” (Mayor’s Office of Transportation 1978, 5).

The Hackney Carriage Unit of the Boston Police Department licenses and regulates Boston's taxicabs, and as of 2011, Boston licensed 1,825 taxicab medallions—a quantity that has remained fixed since the late 1990s. Boston's ratio of taxicabs per capita is the fifth highest among American cities that have at least 1,300 taxicabs, with slightly more than three taxicabs in Boston for every 1,000 residents (Schaller 2006).

The taxicab market in Boston comprises more taxicabs than the 1,825 licensed by the City of Boston, however, as the municipalities that surround Boston also license taxicabs individually. Cambridge, for example, licenses 257 taxicabs, while Brookline licenses 187. Each municipality regulates its taxicabs separately and rates are not consistent throughout Boston's metropolitan area. While Boston itself accounts for many more taxicabs than any single nearby town, taxicabs licensed by the towns that neighbor Boston add up to a significant share of the area's total. This plurality does not serve a unified market, as each municipality's taxicabs, including Boston's, primarily pick up passengers in that municipality but transport them to any requested destination.¹⁰ Boston taxicabs are, in fact, legally prohibited from picking up street hail passengers outside of Boston, and suburban taxicabs cannot pick up street hail passengers within Boston. As a result, taxicab service between Boston and its suburbs is asymmetrical, with Boston taxicabs providing high levels of outbound service and suburban taxicabs providing disproportionate inbound service.

¹⁰Due to the airport's location within city limits, Boston taxicabs pick up most passengers from Boston Logan International Airport while any municipality's taxicabs can drop off passengers there. Airports are typically major sources of taxicab demand within metropolitan areas, so this has a significant impact on Boston's taxicab market.

REGULATION OF BOSTON TAXICABS

Boston regulates its taxicabs in a variety of ways. The Boston Police Department's Hackney Carriage Unit was founded along with the Police Department in 1854 and licenses taxicabs under the authority of the Acts of 1930. The Inspector of Carriages, a Boston police officer, commands the unit. Two components of Boston's taxicab regulation have especially great impacts on the industry: fares and medallions.

Fares: As many other cities do, the City of Boston sets precise fares for its licensed taxicabs, with meter rates determined by distance traveled. As of January 1, 2011, the following rates applied:

- \$2.60 for the first 1/7 mile (the "drop rate")
- \$0.40 for each 1/7 mile thereafter, plus tolls
- \$28.00 per hour for idling or waiting
- \$2.75 toll paid for trips from Boston proper to either Logan Airport or North Shore Communities
- No toll for trips from Boston proper to East Boston

These meter rates apply to all taxicab trips by Boston licensed taxicabs within Boston as well as trips between Boston and more than 90 surrounding municipalities, while a handbook of flat rates (calculated at \$3.20 per mile) governs destinations beyond that range.

The difference between Boston's "drop rate" (the initial amount charged for every trip) and its mileage rate has different implications for different trip distances. The inflexible drop rate is spread across a trip's total distance, so higher drop rates and lower mileage

rates favor longer-distance trips on a cost-per-mile basis. Conversely, a low drop rate and high mileage rate favors short-distance trips. The Mayor's Office of Transportation (1978) observed that raising the mileage rate relative to the drop rate benefits passengers traveling short distances and "especially those who depend on taxis for necessary trips," while also creating an incentive for drivers to serve the airport where trips are typically longer (7). The study also notes that this system is disadvantageous for taxicabs serving low-density areas when demand in those locations is mainly for shorter trips.

Historically, Boston has adjusted the taxicab drop rate and mileage rate by different percentages. The City's most recent adjustment, which raised fares to the rates listed above, became effective in early 2009. That adjustment increased the drop rate by 1 percent (from \$2.25 for the first 1/8 mile) and increased the mileage rate by 17 percent (from \$0.30 per 1/8 mile). The City justified this fare increase on the basis of rising fuel costs. During the past several decades, Boston's drop rate (per mile) has increased far more than its mileage rate: In 1978, the drop rate was \$0.60 for the first 4/9 mile and the mileage rate was \$0.10 for each subsequent 1/9 mile (Mayor's Office of Transportation 1978). Boston's taxicab fares are also higher than those of comparable cities, in general. Its drop rate and mileage rate are both higher than New York's, while only its mileage rate is higher than Chicago's.

Medallions: Medallions directly impact the supply of taxicab transportation in Boston, imposing a ceiling on the size of the industry. The Boston Police Department (2008) defines a medallion as "a license granted to a suitable individual to operate a vehicle as a Hackney Carriage in the City of Boston" (3). Although a medallion belongs to an individual, it corresponds to a specific vehicle, or Hackney Carriage, and must remain

attached to that vehicle at all times. As mentioned above, Boston currently licenses 1,825 taxicab medallions. Unlike fare rates, however, the quantity of available taxicab medallions has only been adjusted once in Boston. The limit of 1,525 medallions that the Massachusetts legislature enacted in 1930 remained effective until the 1990s, when a protracted legal battle led the City to increase that number to the 1,825 medallions that are presently available.

Aside from fixing the supply of taxicabs in Boston and limiting entry into the industry, medallions, which are transferable, have attained considerable free market value in Boston and other cities. Boston's 1,825 medallions constitute the third largest medallion market in the United States after New York and Chicago. FareInvestor, a website that aggregates and publishes information about taxicab medallion investment and license transfers, estimated the market value of a Boston taxicab medallion to be \$385,000 in late 2009. The high value of a single medallion constrains opportunities to reform the taxicab industry: A medallion represents a significant investment, the value of which would be diluted by deregulation, so existing medallion holders have a vested interest in restricting market entry.

The Depression-era origins of taxicab market entry restrictions in Boston and in other cities received attention in the previous chapter, but the present wisdom of these policies has been a subject of much debate. While Cervero (1997) has identified cases where taxicab deregulation has brought about net benefits, Schaller (2007) makes the following point:

“Geographic imbalances in service tend to arise whenever higher trip densities prompt drivers to cluster in downtown business and commercial districts and airports in preference over outlying areas. Geographic

imbalances were seen in cities that deregulated as well as cities that control entry... Thus, market characteristics rather than regulatory policies underlie the problem of geographic imbalances.” (12)

In Boston, which exhibits the conditions Schaller describes, medallions and restricted market entry may not be the most significant cause of the service gaps this thesis investigates. If Schaller's assessment is correct, market deregulation would do little to discourage spatial imbalances in taxicab service. The various forces to which he refers, however, require further analysis that would strengthen or weaken his claim. The remainder of this thesis investigates the specific factors that may influence the spatial distribution of taxicab activity.

C. Summary

This chapter and the previous chapter bring together general principles of the taxicab industry and the specific conditions that make those principles applicable to Boston. The purpose of these chapters has been to illustrate the taxicab's importance to urban mobility, its relationship to other urban transportation modes, and the particular opportunities and constraints that the taxicab encounters in one city. The remainder of this thesis will directly address the question of how taxicab service is distributed throughout Boston, frequently drawing upon the preceding chapters' foundation. As I have argued thus far, the taxicab is an important transportation mode in Boston and in many other cities, and is uniquely suited to contribute to mobility in densely populated urban areas by complementing other modes. In the following chapters, I attempt to determine whether the taxicab successfully makes that contribution in Boston, considering the forces that influence its operation there. Answering that question can ultimately inform changes to the taxicab industry that might enable the taxicab to fulfill

its potential. If the taxicab does not serve certain parts of Boston that it is well-suited to serve, we must inquire whether this occurs due to the structural limitations of these taxicab operations or due to a lack of demand for the mobility the taxicab provides.

IV. DATA AND METHODOLOGY

This chapter explains in detail how I will answer the central questions about taxicab service distribution in Boston that this thesis asks: How is taxicab service distributed throughout the city, and to what extent does the taxicab act as a complement to or substitute for mass transit? The chapter's first section addresses the concept of realized taxicab demand, its relationship to total demand, and how limited knowledge of the latter constrains this analysis and its conclusions. The second section describes the taxicab trip data upon which the analysis relies, while the third section describes the research scope in greater depth. The fourth and final section of this chapter outlines the research methodology, its purpose, and its limitations.

A. Treatment of demand

REALIZED DEMAND

One key limitation of this analysis, and of many transportation studies, is the difficulty of knowing general or mode-specific travel demand with any certainty. The second chapter's discussion of taxicab economics alluded to this predicament: Trips represent *realized demand* or a clearing of the market for travel. In other words, a trip occurs when transportation services charging a certain price encounter passengers for whom the relative utility of those services exceed the utility of other available options (including the option of not traveling at all).

If one interprets the *generalized cost* of transportation as a combination of a trip's monetary and non-monetary (time) costs, then the spatial and temporal availability of a

mode become important factors that influence when and where the market for that mode clears. One individual might make a trip that requires a \$2 fare and 20 minutes of travel time, but another might forgo the same trip despite a willingness to travel if the generalized cost were lower. Both are instances of travel demand, but only one represents realized demand.

Realized demand is a function of supply as well as demand, a fact that manifests itself critically in taxicab markets. Because taxicab operations and service availability are more flexible than for other urban transportation modes, with no fixed routes or schedules, expected wait times for taxicabs are theoretically less predictable than they are for those other modes. Mass transit is a prime example of a more predictable mode: It does operate according to fixed routes and schedules (although its service does not always adhere reliably to the latter), allowing passengers to estimate expected wait times with some accuracy and predict their total travel times and costs accordingly. Likewise, travel by car and bicycle impose negligible waiting times if passengers own the vehicle, as they usually do (although in-vehicle travel times vary due to traffic congestion).

In contrast to these modes, taxicabs circulate freely, respond to dispatch requests, or queue at taxicab stands. For the traveler without a car or bicycle, the three most widely available modes in a city like Boston are mass transit, taxicabs, and walking; of those three, only taxicab trips' generalized costs depend upon a spatial distribution of service that, in theory, can vary unpredictably by time of day. If one begins a trip near a bus route, he can expect a bus to eventually arrive along that route, but no such formalized expectation applies to taxicabs (although a taxicab's arrival may be quite predictable in many places). In the short term, moreover, taxicab service can redistribute itself as

transit cannot, with a corresponding redistribution of expected waiting times. Rail and bus transit typically require centralized planning decisions, infrastructural expansions (in the case of rail), or increases in vehicle fleet size in order to achieve similar outcomes.

Higher levels of taxicab service at a specific location and time should lead to more realized demand, all else being equal. At any given time, a city's map of expected generalized costs for transportation overlays a map of passengers' willingness to pay for travel, as determined by the relative utility that specific trips offer those passengers. In situations where willingness to pay exceeds that generalized cost, passenger demand will manifest itself as realized demand; when generalized cost exceeds willingness to pay, it will not. Because taxicab fare rates are fixed in Boston, generalized costs for taxicab trips vary primarily by their non-monetary components in the form of expected waiting times: Areas with high concentrations of cruising taxicabs can have expected wait times that are reliably close to zero at certain times of day, while other locations may rarely see cruising taxicabs and rely upon dispatching for much of the service they do obtain. Equivalent concentrations of taxicab demand should therefore generate more trips, or instances of realized demand, in areas with better taxicab service.

WHAT WE CAN LEARN FROM REALIZED DEMAND

Realized demand and its divergence from overall demand are problematic for this analysis, which studies the movement of taxicabs and the spatial distribution of taxicab trips that actually occur but does not directly examine the qualities of passengers themselves. The central question of this thesis concerns the taxicab's role in Boston, and the data employed to answer that question are records of realized demand rather than total demand. Potential passengers who desire mobility but forgo travel due to its

generalized cost are important urban transportation system stakeholders whose presence is not reflected in ridership patterns.

Demand is derived from passengers and their preferences as well as transportation service itself, but the data that enable this analysis illuminate characteristics of the latter and not the former. One may infer some qualities of taxicab users from trip data, though. Origin and destination, payment by cash or credit card, total fare, and tip may all be correlated with certain passenger characteristics (income, car ownership, status as tourist or local resident). Characteristics of trip origins and destinations may also provide clues about the passengers themselves. Only additional data collection in the form of passenger surveys or a similar method, however, would confirm these inferences.

Despite these limitations, data on realized taxicab demand can tell us the following:

- Which locations do receive taxicab service, and to what extent.
- Travel patterns of passengers who are willing to pay.
- Which purposes the taxicab is actually serving.

Corresponding to these points are questions that realized demand cannot answer so easily:

- Which locations are underserved by taxicabs, possessing a reasonable concentration of travel demand but insufficient levels of taxicab service?
- Which locations do not receive taxicab service due to lack of demand?
- Which locations (and which groups of people) *should* the taxicab serve that it currently does not, and what types of travel would those groups demand?

While this thesis cannot fully account for the uncertainties that unmet demand creates, the question of the taxicab's actual and ideal roles in urban transportation requires acknowledgement of the groups that must benefit more from taxicabs than they currently do—the marginal users that better service would convert into realized demand. If taxicabs must fill the gaps in mass transit systems, as suggested in Chapter Two, then it becomes important to estimate the levels of unmet demand located in those gaps—demand which the taxicab might meet more economically than transit in many cases.

I do not attempt to precisely quantify unmet taxicab demand in this thesis. Rather, my analysis closely examines Boston's taxicab activity, or realized demand, in the context of its current roles as transit complement and substitute. Having accomplished this, I proceed to examine the characteristics of areas within Boston that the taxicab serves poorly in its capacity as a complement to mass transit. Populated areas that lack taxicab and mass transit mobility alike, which exhibit characteristics that suggest the presence of captive riders as Chapter Two defines them, will emerge as the most likely locations that taxicabs underserve. The concentration of unmet demand in those areas will not be proven, but assessing that concentration will be suggested as a productive subject of future research. The task of examining realized demand alone is a necessary prerequisite to answering that question, however, and answering both questions would be too large a task for this thesis to effectively accomplish.

B. Scope

As discussed in previous sections, this analysis confines its scope to the 1,825 medallion taxicabs licensed by the City of Boston—the taxicabs for which detailed trip level data have been collected since 2009. Municipalities adjacent to Boston, such as

Cambridge, have substantial taxicab systems of their own with separate regulatory constraints and licensing mechanisms, and these taxicabs frequently carry passengers to and from Boston along with Boston's own licensed taxicabs. The activity of these taxicab systems has important implications for Boston's system, because they serve many of the same origin-destination pairs as Boston taxicabs, but the lack of available trip-level data for these systems precludes their close examination here. This issue receives a more detailed treatment below.

GEOGRAPHIC SCOPE

Although this research focuses on Boston's taxicabs, its full geographic scope extends well beyond the city's borders, as Boston taxicabs must serve any requested destination from Boston. Data show taxicab trips with destinations as remote as Cape Cod, 70 miles from Boston, and the City's official flat rate handbook lists fares for destinations throughout the Northeast. Different levels of analytical detail are possible at two separate scales:

- Trips that both begin and end in Boston
- Trips that either begin or end outside of Boston

The first category, trips that both begin and end in Boston, can be studied at the highest level of detail using Boston taxicab data, because Boston taxicabs serve the vast majority of these trips. Available taxicab trip data will almost completely capture this category, which comprises approximately 82 percent of trips by Boston taxicabs in the four-weekday sample examined here.

The second category of trips, those which begin or end outside of Boston, is reflected less accurately in Boston taxicab data. Because many other taxicab systems serve Boston from the municipalities that surround it, as discussed above, the Boston taxicab trip data reflect a less complete portion of the total activity between Boston and its environs. In particular, the Boston trip data suggest that a given municipality's own taxicabs will disproportionately serve trips that originate there and end elsewhere. Table IV-1 shows that Boston taxicabs serve a significantly higher share of outbound trips, which begin in Boston and end elsewhere, than in the inbound direction, with the inverse imbalance presumably applying to other municipalities' taxicabs. This makes sense, because a city's own taxicab supply finds the majority of passengers it can serve within that city.

Table IV-1: Boston taxicab trips beginning and ending within Boston

	Boston origin	Boston destination	Boston origin and destination
May 12 2010	97.6%	83.4%	82.1%
Aug 4 2010	97.8%	84.2%	83.0%
Oct 20 2010	97.2%	82.2%	80.8%
Jan 26 2011	97.1%	84.0%	82.6%
Average	97.4%	83.4%	82.1%

This analysis studies Boston taxicabs' trips beyond city limits with the understanding that the available Boston taxicab data do not fully reflect total taxicab activity in this market. Suburban trips by Boston taxicabs cannot be ignored, after all: This thesis inquires how Boston's taxicab system aligns with its mass transit network, and the MBTA serves many other municipalities in addition to Boston. Transit access between Boston and Cambridge, for example, must be compared with taxicab activity between the two cities to the most accurate degree possible. Because taxicab pickups are a

better indicator of the mode's service levels than drop-offs are, and because levels of service within Boston are the ultimate object of this study, taxicab trips that originate outside of Boston are necessarily excluded from analysis. Only 2.6 percent of trips by Boston licensed taxicabs begin outside of Boston in the four-day sample I use, however, so the majority of Boston taxicab activity still receives consideration under that constraint. In summary, this thesis considers two trip categories—Boston-to-Boston trips and Boston-to-suburb trips—with a small percentage of trips in the second category possibly fulfilled by other municipalities' taxicabs. Thus, Boston taxicab data should provide nearly complete samples for both categories.

DATES AND TIME SPANS

I study four 24-hour weekday periods of taxicab activity in this analysis. The large volumes of daily taxicab activity in Boston, the difficulty of processing larger quantities of these data, and the general consistency observed across four separate days justify this sample size. The following four days, which compose the sample, are all Wednesdays; every taxicab trip that begins between midnight and 11:59 p.m. on each date is included in that date's selection (meaning that some included trips begin just before midnight and end on the following day):

- May 12, 2010
- August 4, 2010
- October 20, 2010
- January 26, 2011

These four dates are spaced evenly throughout the calendar year (although not precisely three months apart) and omit holidays that would potentially distort typical

weekday demand patterns. The spacing of these four dates captures any seasonal variations that may exist in taxicab activity, including the influence of academic institutions in Boston that reduce their activity during the summer. All four days are Wednesdays to maximize consistency, although no major variations among different mid-week days are hypothesized.¹¹ Weekends, of course, exhibit very different transportation (and taxicab) ridership patterns than weekdays, but analyzing weekend ridership is a subject for a separate analysis.

Weather is a relevant determinant of taxicab demand, as rain and cold make walking, bicycling, and mass transit less appealing than they otherwise would be while encouraging taxicab use. On the four days I study, weather is relatively consistent: No precipitation or cold weather was recorded in Boston on May 12, August 4, or October 20 in 2010. On January 26, 2011, the temperature was near or below freezing throughout the day, with light snow throughout the afternoon and evening and about two hours of rain late in the day (Weather Underground 2011). Because these weather conditions were confined to the winter observation day in my sample, and because light snow is likely to have less impact on taxicab demand than rain would, I expect that seasonal differences in taxicab activity will largely capture the effects of this weather.

¹¹ Professional sporting events do occur in Boston on these four sample days, although no significant distortion in taxicab activity appears to result from this. The Red Sox played home games at Fenway Park on May 12, 2010 and August 4, 2010, in the afternoon and evening, respectively. The Celtics played a preseason home game on the evening of October 20, 2010 at the TD Garden. The Bruins played an evening home game at the TD Garden on January 26, 2011.

Finally, because the chief purpose of this thesis is to examine Boston's current patterns of taxicab activity, I have deemed the preceding year sufficient for analysis. The taxicab data I use are only available beginning in mid-2009 and data collection had not been extended to cover the entire taxicab system during the months that followed its initial implementation. Thus, confining the analytical scope of this thesis to the preceding year maximizes the integrity of these data.

C. Data

The data that form the foundation of this analysis are records of trips made by Boston taxicabs. The mandatory installation of rear-seat, self-swipe credit card payment devices in every Boston taxicab in 2009 gave the City the capacity to digitally record detailed information about every trip, regardless of a customer's actual payment method. Two separate providers, Creative Mobile Technologies (CMT) and Verifone, implemented this technology in Boston's taxicabs and manage the data collection process.

Each taxicab trip record comprises a number of trip characteristics, the most important of which for this thesis are the following:

- Taxicab medallion number
- Pickup location (latitude and longitude)
- Drop-off location (latitude and longitude)
- Pickup time and date
- Drop-off time and date
- Trip fare
- Tip

- Tolls and extras

In the research presented here, the availability of pickup and drop-off times, dates, and locational coordinates are especially critical. The trips' spatial coordinates facilitate the mapping of taxicab pickup and drop-off locations throughout Boston and its surroundings using GIS software and provide a level of insight into taxicab activity that was unavailable before a combination of sufficient technology and its widespread application enabled this type of data collection. The full set of these taxicab trip records reside in two separate databases belonging to CMT and Verifone, respectively.

TAXICAB DATA LIMITATIONS AND EXCLUSION

The relative completeness, precision, and detail of the trip data provided by CMT and Verifone does not, of course, mean that the data are perfect. The massive sample size available for any given day in Boston, however, does mean that a large sample of taxicab trips remains usable even if incompleteness forces the exclusion of some data.

Certain basic rules inform the choice of which data to exclude from analysis. The research objectives of this thesis give certain trip characteristics priority over others, as acknowledged above: origin and destination coordinates, trip times and distances, and fares assume the greatest importance and must be most accurate. Minor inaccuracies in these data are not known with certainty, but I exclude taxicab trips at various points if they exhibit the following characteristics, due to these values' high probability of inaccuracy:

- **Missing origin or destination coordinates (excluded from all analysis):** All taxicab trips lacking latitude and longitude coordinates for either their origins or

destinations are excluded from this analysis. The importance of taxicab trips' spatial locations to my inquiry makes this information the most critical, as records lacking origin or destination coordinates cannot be mapped.

- **Missing trip distance (excluded from descriptive statistics):** All trips with a distance equal to zero are excluded from trip distance calculations due to the impossibility of an actual trip having zero distance. Some instances of this value may represent trips that never actually happened due to a passenger boarding before deciding not to make the trip, but most records with zero distance display nonzero fares or travel times, which suggest otherwise.
- **Low fare (excluded from descriptive statistics):** Because the base fare for a Boston taxicab trip is \$2.60, a recorded fare should not be lower than this value. Any trip record indicating a fare lower than \$2.60 is therefore excluded from average fare calculations, although, as with trip distance, there may be occasional explanations for this occurrence.
- **Short trip duration (excluded from descriptive statistics):** Trip duration, calculated using a trip's start and end times, provides a basis for a trip's exclusion if equal to zero. I exclude these trips from trip characteristic calculations for the same reasons as trips with zero distance. Interestingly, a negligible number of trips lacked start or end times altogether (perhaps because the database query I used would not have retrieved such trips).

Table IV-2 indicates the frequency of each missing characteristic in the four-day sample and the total number of trips excluded due to missing coordinates. As the table shows, 89 percent of trip records have complete coordinates and are usable for much of the analysis that follows. A mapping of trips with complete geographic coordinates that lack other characteristics suggests that no significant bias exists in the excluded data, with

the possible exception of outliers that are most likely inaccurate. The majority of excluded trips appear to be actual trips that were simply not recorded completely; thus, I interpret the pre-exclusion trip totals as reasonable approximations of real daily trip totals. To estimate the aggregate characteristics of those trips, however, I exclude data with the characteristics listed above. Overall, 79 percent of trip records have complete coordinates as well as complete trip characteristics, and this smaller data set is what I use to calculate average fares, trip distances, and other trip characteristics by block group or hour.

Table IV-2: Data exclusion percentages

	Total	Missing Coordinates	Trip distance*	Low fare**	Trip time***	Complete Coordinates	% of Total	Complete Coordinates + Characteristics	% of Total
May 12 2010	37,441	4,324	5,024	66	313	33,117	88.5%	28,024	74.8%
Aug 4 2010	33,233	3,652	4,636	54	204	29,581	89.0%	24,881	74.9%
Oct 20 2010	34,953	3,937	2,127	89	286	31,016	88.7%	28,829	82.5%
Jan 26 2011	34,161	3,475	1,882	87	193	30,686	89.8%	28,766	84.2%
Average	34,947	3,847	3,417	74	249	31,100	89.0%	27,625	79.0%

* If trip distance = 0

** If trip fare < \$2.60

*** If trip time = 0

One final limitation of these taxicab trip data that bears mentioning is the prevalence of zero counts in the sample observations. Table IV-3 gives the number of block groups that show zero values for each dependent variable (trip generation and transit substitution) during the relevant time periods. As the table demonstrates, zero counts for both variables are quite common during any observed three-hour window on a single day. The dependent variables in all regression models I specify are four-day averages for block groups and time periods, however, so zeroes never account for more than one

third of average trip counts in those models. Zero-inflated Poisson regression is one technique available for modeling data with high zero counts, and this method reflects the existence of a fundamental difference between zero and nonzero observations. I choose not to use this method here, but it could offer more explanatory power than a straightforward Poisson regression if a fundamental difference between zero-count block groups and trip-generating block groups is hypothesized. For transit substitution, in which zero counts are above 50 percent for even the four-day averages, I address the zero counts by using Tobit regression, which I explain in the following section.

Table IV-3: Zero counts in taxicab trip data (by block group)

		Total Zero Count (544 observations)				% Zero Count			
		Night	AM	PM	Evening	Night	AM	PM	Evening
Total trip generation	May	344	238	306	314	63%	44%	56%	58%
	Aug	330	227	277	319	61%	42%	51%	59%
	Oct	361	224	299	325	66%	41%	55%	60%
	Jan	342	203	280	287	63%	37%	51%	53%
	Avg Day	178	70	139	163	33%	13%	26%	30%
Transit substitute trip generation	May	544	409	424	411	100%	75%	78%	76%
	Aug	544	412	419	434	100%	76%	77%	80%
	Oct	544	403	422	419	100%	74%	78%	77%
	Jan	544	385	410	342	100%	71%	75%	63%
	Avg Day	544	320	344	402	100%	59%	63%	74%

D. Methodology

This thesis proceeds through three phases of analysis in its examination of the Boston taxicab system. In the first phase, I map the distribution of taxicab activity throughout

Boston and its environs in an effort to understand the broad spatial and temporal patterns of the mobility that the mode provides. In the second phase, I examine Boston's taxicab activity in the context of the city's mass transit network, with the preliminary purpose of categorizing taxicab trips as either substitutes or complements to mass transit. Following this trip categorization, I map the spatial and temporal distributions of those two categories.

In the third phase of analysis, I specify two sets of models for taxicab trip generation within Boston. The first set regresses taxicab pickup counts by census block group, a dependent variable, on characteristics of those trips' origins, including population, land use patterns, and transit access. Separate models are specified for four different times of day. The second set of models regresses the share of a block group's taxicab trips that are transit substitutes (as defined here) on a similar set of independent variables. Again, separate models are specified for different times of day. These two sets of models highlight the factors that are correlated with taxicab service levels and illuminate the taxicab's role as a transit substitute or complement in Boston while also helping to identify areas within the city that taxicabs potentially underserve. A more detailed discussion of each of these three phases follows, along with an initial description of key analytical parameters.

UNITS OF ANALYSIS

The spatial unit by which I aggregate taxicab trips matters greatly to this analysis. A variety of spatial units are available within Boston and its surroundings, and each has distinct advantages as well as disadvantages. Any spatial unit must be small enough to capture variations within the city's 48 square miles of land area, in which the majority of Boston's taxicab trips begin and end, but large enough to comprise more than a handful

of taxicab pickups and drop-offs. The following units are considered, although census block groups are the units that I ultimately select:

- **Census blocks:** The City of Boston comprises approximately 5,500 census blocks with an average area of 0.01 square miles each. The census block's primary advantage as a unit of analysis is the level of detail it reveals—many blocks coincide with actual city blocks. Census blocks have important limitations, though: First, they may provide too fine a resolution. Their small size means that many blocks will contain no taxicab pickups, and drawing conclusions from data aggregated at this level will be difficult. Likewise, an area's access to taxicab service has more meaning at a larger scale: Minimal taxicab access within one census block means little if better access is available in a nearby census block. Finally, because census block boundaries typically align with streets, where taxicab pickups and drop-offs actually occur, the allocation of any taxicab trip to one block or another will often be deceptive.
- **Census block groups:** Census block groups offer the same advantages as census blocks, with the additional advantage that sample census data as well as "100-percent" characteristics are collected at this level. Each census block group contains a set of census blocks, and Boston itself comprises approximately 545 block groups with an average area of 0.09 square miles each. This scale is preferable to the smaller scale of census blocks for the reasons explained above. Census block group borders also align with roads but because they are larger than individual census blocks and contain more roads that are entirely within their borders, this occurs less frequently.
- **Traffic analysis zones (TAZ):** The TAZ is a spatial unit similar to the census block group and is commonly used in transportation analysis and modeling. A

TAZ is usually made up of census blocks or block groups, so the advantages and disadvantages of those units also apply to TAZs as well. Because the TAZ is a popular unit for transportation analysis, it would be appropriate here, but the simplicity of using census block groups slightly outweighs this benefit.

- **Grid cells:** Unlike the two preceding groups, the grid cell is an arbitrary unit with no relationship to Boston's urban form. A grid cell of any size is standardized with borders independent of the urban street grid, unlike census blocks or block groups, offering the advantage of capturing more taxicab trips that coincide with streets. Grid cells are problematic, however, because census data are not aggregated by this unit and are difficult to allocate meaningfully where grid cells span multiple census block groups.

The strengths and weaknesses of each spatial unit discussed above favor the census block group for this analysis of taxicabs. The block group's appropriate scale and alignment with census data outweigh the inconvenience posed by streets that follow the unit's boundaries. Boston comprises 545 census block groups, and I exclude one of these, block group 107437, from analysis because it covers Boston's Harbor Islands, which are mostly inaccessible by car and thus outliers in a study of taxicab activity. For the rest of Boston's block groups, most taxicab trips along the block groups' edges will be randomly allocated between two groups, but that allocation will generally occur in an unbiased fashion. Furthermore, taxicab activity along a block group's edge has significance for the adjacent group, so the division of edge trips between two groups is a reasonable approximation of reality, given the constraints imposed by this level of aggregation.

PHASE ONE: INTRODUCTION TO TAXICAB RIDERSHIP PATTERNS

Before categorizing taxicab trips as mass transit substitutes or complements, the basic patterns of Boston's overall taxicab activity must be understood. The first phase of taxicab trip analysis entails a detailed mapping of Boston's taxicab activity that focuses on the following aspects of that activity:

- **Pickups and drop-offs by location, time of day, and season:** Mapping the spatial distributions of taxicab pickups and drop-offs throughout Boston and its environs reveals patterns that serve as the first step toward grasping the taxicab's present role in the city. These patterns also reveal, in a general and intuitive sense, which areas appear to have surpluses or shortages of taxicab service. Before introducing additional trip characteristics or linking origins to destinations, pickups and drop-offs are displayed separately. Additionally, the variations in these distributions and in overall trip quantity by time of day or by season indicate how taxicabs serve the city differently throughout the year.
- **Trip distances and travel times:** This thesis repeatedly emphasizes that travel time is a component of a trip's generalized cost and therefore a factor that influences who will be willing to pay for that trip. Taxicab trip durations, distances, and average speeds, which all vary throughout Boston and correlate with one another, contribute to an understanding of how taxicabs are used differently throughout the city. The relationship between average trip distance and the ability to make the same trip on foot, furthermore, helps to distinguish one type of choice rider from captive riders.
- **Fares:** Boston's taxicab fares are distance-based and its fare rates are fixed, so monetary fares vary according to trip distance. Nonetheless, several other factors

introduce additional variability to taxicab fares. Tolls and extras, which impact airport trips most noticeably, increase certain trips' fares beyond what trip distance dictates. Voluntary tips from passengers have similar effects on total fares. Neither tips, tolls, nor extras will be evenly distributed throughout Boston, so the incidence of each provides important insight into the citywide fluctuation of taxicab trip costs. Finally, because Boston taxicabs charge \$2.60 for a trip's first 1/7 mile and only \$0.40 for each additional 1/7 mile, a trip's fare per mile will be greater for short trips than for long trips.

- **Balance of pickups and drop-offs:** Taxicab trips indicate realized demand but not unmet travel demand. The asymmetry between the spatial distribution of taxicab pickups and drop-offs represents an opportunity to identify one type of unmet demand, however. The Design Trust for Public Space (2007) writes,

“A cab driver can be likened to a pinball in a pinball machine—the driver goes where the passenger directs and then picks up the next rider on a rebound, ideally as close as possible to the previous drop-off point...If no passengers direct a cab to (a) location then people waiting in that area will find it difficult to hail a cab.” (118)

In other words, taxicabs cruise where they expect to find passengers who are willing to pay, but take those passengers to any destination they request. In general, Boston taxicab data reveal a relative concentration of taxicab pickups and a more diffuse pattern of drop-offs. Access to taxicab service is most likely poorer in areas where drop-offs exceed pickups: Round trips are more likely to end than begin in these block groups (assuming the majority of travel demand is for round trips), meaning that the generalized cost of a trip that begins in such a block group is most likely higher than for its inbound counterpart and that

demand in that direction is realized less frequently. For taxicabs, the asymmetry in a round trip's generalized cost would primarily result from unequal waiting times due to different service levels at each leg's point of origin, and less realized demand in one direction would reflect lower service levels. Of course, this generalization will not always hold true, and further analysis is necessary to draw these conclusions with any confidence from a block group's balance of pickups and drop-offs.

Combining and averaging the taxicab trip data from four separate weekdays in 2010 and 2011 enables a detailed portrayal of taxicab activity in Boston using the metrics just described and creates a necessary foundation for the analysis that follows in the second and third phases.

PHASE TWO: CATEGORIZATION OF TAXICAB TRIPS

Following the first phase's initial description of Boston's taxicab activity, the second phase of analysis introduces the main question of this thesis: Does the taxicab function as a substitute for mass transit or a complement to it? While the third phase specifies the model that attempts to answer that question directly, this phase separates taxicab trips into two categories, transit substitutes and complements, based upon whether a reasonable transit alternative was available for that trip. Several preliminary categorizations will inform the ultimate division of trips into transit substitutes and complements. All Boston taxicab trips will be counted as one of the following in each of four category pairs:

- Trip originating in Boston or outside of Boston
- Walking substitute or complement

- Airport or non-airport trip
- Transit substitute or complement

A more detailed description of these categories follows, including a discussion of each category's relevance to my research objectives and an explanation of how I will identify the trips belonging to these groups. Each of the four pairs is mutually exclusive and collectively exhaustive.

Trips originating in Boston or outside of Boston: The two principal categories into which I divide Boston taxicab trips are those that begin in Boston and those that begin outside of Boston. The reason for categorizing trips in this way is discussed above: Taxicab service levels, which impact waiting times, generalized travel costs, and realized demand, affect individual taxicab trips at their origin locations. A taxicab trip's destination, on the other hand, is unknown by the driver in advance and only becomes relevant once that passenger has successfully obtained taxicab service. Thus, understanding taxicab service levels within Boston requires analysis of trips that begin in Boston; trips that begin elsewhere and terminate in Boston primarily impact the level of service in their suburban locations of origin.

Sorting trips according to this criterion is straightforward. Any Boston taxicab trip that begins in a Boston census block group (97.9 percent of the four-day sample I use) is included in the universe of trips I analyze, while those that begin elsewhere are excluded from analysis. Again, some suburban taxicabs that this Boston taxicab data set omits will pick up their passengers within Boston, but these trips' share of total Boston pickups is expected to be quite small and no data are available to precisely quantify these trips.

Walking substitutes or complements: Transit’s ability to serve a particular origin-destination pair determines whether a taxicab trip acts as a substitute for that trip, but walking—another alternative mode for which the taxicab can substitute—is primarily limited by trip distance. Unlike transit, which cannot effectively serve trips that do not begin and end within its service area, walking is equally available to most individuals at any location, although characteristics of the traveler as well as the trip’s location can limit the ability to walk. Additionally, transit (especially rail) does not make sense for shorter-distance trips. A transit line’s travel time, fare price, and distance from a trip’s origin and destination are decreasingly competitive with walking as that trip’s distance decreases.

Because user characteristics fall outside the scope of this analysis, I simply define a walkable trip as any trip of less than 0.5 miles.¹² Any uniform walking distance is arbitrary, of course, but literature on transit-oriented development has previously employed the 0.5-mile walking distance assumption (Bossard et al. 2002). Many short-distance taxicab (or mass transit) trips will not, in reality, reflect a choice between the taxicab and walking.¹³ For this analysis, however, treating all short-distance trips as potential walking substitutes is the best possible assumption since it will hold true for the

¹² This measurement refers to actual trip distance, as provided by taxicab trip records, and not the straight-line distance between origin and destination points.

¹³ As with airport trips below, many short-distance trips by taxicab will reflect circumstances that restrict mode choice. Luggage, a tourist’s unfamiliarity with Boston, or an individual’s high valuation of time are a few such examples.

majority of passengers, and the 0.5-mile constraint places an upper bound on the quantity of taxicab trips that could also be made on foot. Trips that would otherwise be classified as transit substitutes (see below) will therefore not be classified as such if their total distance is less than 0.5 miles.

Airport or non-airport trips: An additional criterion by which I sort taxicab trips is whether or not a trip begins or ends at Boston Logan International Airport. Airport trips must be distinguished from other trips for an important reason: The characteristics of airport trips differ significantly from other trip types, as these passengers typically carry luggage and value travel time and punctuality more than they would under normal circumstances. Additionally, airport passengers are often tourists with higher willingness to pay for travel and less familiarity with Boston or its transit system in comparison with their local counterparts.

Boston's airport is directly accessible by mass transit via the Silver Line and indirectly accessible via the Blue Line, but for the reasons just listed, airport trips that fall within transit's service area are not considered transit substitutes here. The task of sorting trips as airport and non-airport trips is therefore quite easy: Any trip that begins or ends within census block group 106955, which coincides with Logan Airport, is classified as an airport trip.

Mass transit substitutes or complements: The most crucial taxicab trip characteristic for this analysis is the trip's status as a transit substitute or complement. This distinction received treatment in Chapter Two: A taxicab trip that is a substitute for transit is one that could reasonably have been made by transit, given its origin, destination, and time of day. A complement for transit, conversely, has an origin and destination that transit does not directly link or occurs at a time when that service is not available. The

definition of mass transit's service area therefore determines which taxicab trips are substitutes for transit and which are not. Several informed assumptions contribute to the definition of transit service area in this analysis. Regardless of that definition, however, a transit-substitute taxicab trip must begin and end within transit's service area, and transit must link that particular origin and destination at a suitable level of service with an acceptable number of transfers.

I provide separate definitions for rail and bus substitutability, as the two modes of transit offer distinct forms of service, and I define the spatial service areas of each in slightly different ways. Furthermore, commuter rail and the THE RIDE (the MBTA-operated paratransit service) are excluded from consideration, as both provide transportation services that differ significantly from those of taxicabs. Commuter rail primarily transports passengers between central Boston's major train stations and suburban municipalities during peak periods, a purpose that taxicabs only serve to a very limited extent (and disproportionately in the outbound direction). Paratransit, meanwhile, restricts its eligible ridership to registered disabled customers (despite close operational similarities to dispatched taxicabs) and is therefore not an option for the great majority of potential travelers.

Trips are classified as transit substitutes if they exhibit the following spatial and temporal characteristics while also satisfying the above criteria (longer than 0.5 miles; non-airport trips):

- **Rail:** Any taxicab trip that both begins and ends within a single MBTA rail line's service area is classified as a substitute for mass transit, provided that the trip begins during that line's span of service. One key assumption here is that transit trips requiring a transfer do not represent a reasonable alternative to taxicab

service. I define each line's service area as the area within a 0.5-mile shortest-path distance (not straight-line distance) from any transit station on that line, in accordance with the 0.5-mile walking distance I cite above. Five MBTA rail lines are studied separately: Blue, Green, Red, Orange, and Silver (which is actually a bus rapid transit line that serves a purpose similar to rail). For lines with multiple branches, taxicab trips are compared against each branch separately. Again, trips of less than 0.5 miles do not count as transit substitutes. Finally, the weekday service span used for each line comes from the schedules' first and last train departure times for each line. For simplicity, a uniform start and end time are applied to each line. In reality, each station and travel direction has a unique service span, but the difficulty of precisely relating these to taxicab trips and the small number of trips affected favor the use of uniform service spans.

- **Bus:** Classifying taxicab trips as bus substitutes is more difficult than for rail, due to the large number of bus routes within Boston and the variance in those routes' service levels. The competitiveness of bus transit with taxicabs is expected to be lower, and fewer people are likely to face a realistic choice between taxicab and bus unless the route is fairly frequent. For these reasons, only MBTA bus routes with average weekday ridership greater than 5,000 passengers are considered as viable taxicab substitutes. In 2009, the following 11 routes with at least a segment within Boston fit this criterion: Routes #1, #15, #22, #23, #28, #32, #39, #57, #66, #86, and #111 (MBTA 2009).¹⁴ Classifying taxicab trips as substitutes

¹⁴ Despite this necessary simplification, however, further analyses would benefit from including all bus routes and examining the roles of specific routes more closely. This analysis examines the relationships

for these routes requires a somewhat crude method: Taxicab trip origins and destinations within the service area of any one of these 11 routes are spatially joined to that route using GIS. Any trip that both begins and ends within the same route's service area during the route's service span is counted as a bus substitute. Again, I assume that no trips requiring transfers are substitutes, and I define a bus route's service area using a 0.25-mile straight line buffer surrounding every route (bus stops are spaced more closely than rail stations and a passenger's origin and destination must be near a bus route for the bus to constitute a reasonable alternative to the taxicab). Finally, I apply a service span of 5:15 a.m. to 1:00 a.m. to all 11 routes—although some routes' actual service spans are slightly (though not much) larger than this—due to the difficulty of isolating the precise service span that would be relevant to each taxicab trip.

between individual rail lines and taxicab activity, while only studying the taxicab's relationship to bus service in the aggregate.

Summary of second phase: The four category pairs just described provide useful insight into the taxicab's role within Boston, especially at higher levels of aggregation. The first category pair, which groups trips by origin location, is least helpful since nearly all taxicab trips begin in Boston; however, it allows us to restrict our sample to those trips that truly reflect Boston's level of taxicab service. The three remaining pairs provide more detailed insight into how the taxicab serves Boston. Across the four sample days, 67 percent of all taxicab trips are either transit substitutes, walking substitutes (less than 0.5 miles), or airport trips, with minor overlap between the latter two categories (some airport trips are less than 0.5 miles). This leaves 33 percent of remaining trips as true complements to public transportation. The next chapter disaggregates these categories by time and location and examines them in greater detail, but the following section introduces the models that facilitate deeper analysis of the taxicab's role as public transportation.

PHASE THREE: ANALYSIS OF TRANSIT SUBSTITUTES AND COMPLEMENTS

Identifying and mapping the taxicab's overall activity along with its relationship to mass transit using the methodology just described raises the central question of this thesis: Do places in Boston with poor transit access also tend to have inferior taxicab service, and does this indicate the presence of unmet demand for mobility? Which parts of Boston are underserved by the taxicab? Boston's core receives very high levels of taxicab service while some peripheral neighborhoods do not, but this difference means little if those peripheral neighborhoods have negligible demand for taxicab transportation as well.

The different roles the taxicab fulfills, however, complicate this question. Referring to Chapter Two again, the taxicab may be more important in areas that lack other mobility

options. Passengers' willingness to pay, which partially depends upon their income, may be lower in less affluent parts of Boston and not fully reflect the taxicab's importance there. Understanding whether transit access improves the likelihood that an area will generate taxicab trips, all else being equal, is a first step toward knowing which role for the taxicab—transit complement or substitute—existing conditions favor. I have established that realized demand is a product of taxicab supply and mobility demand, but taxicabs respond to fairly consistent demand patterns as they circulate Boston. If evidence shows that areas with transit access generate more taxicab trips than comparable areas without transit, this will suggest that, in general, taxicabs are less likely to serve those who lack other public transportation options and might depend upon the taxicab more. The question of whether such an outcome occurs due to a lack of taxicab supply, a lack of travel demand, or both follows from that inquiry.

Model 1: To answer the questions just posed, I use regression analysis to model realized taxicab demand as a product of transit access as well as other temporal and spatial characteristics that influence taxicab activity. By controlling for factors like block group population, centrality, and commercial activity, which are also correlated with transit access, the models specified here isolate the specific relationships between transit and overall taxicab trip generation across census block groups and times of day. Many of these models' independent variables influence taxicab pickup volumes through their impacts on either supply or demand, and this distinction provides evidence of whether taxicab supply or demand is the best explanation when a block group's taxicab activity is lower than expected.

I hypothesize that statistically significant relationships exist between transit access and taxicab trip generation, but I expect the nature of those relationships to vary by MBTA

line and mode (rail or bus). That is, I predict that certain types of transit access will be correlated with higher concentrations of taxicab activity, while other types will exhibit negative correlations with taxicab trip generation. Modeling trip generation indicates whether demand for other “public transportation” modes is also higher where transit is available; however, the second set of models (described below) will inform us of the degree to which that taxicab demand is for origin-destination pairs that taxicabs also serve. The second set of models may reveal, for example, that the travel demand patterns the MBTA Red Line serves are also more desirable to individuals traveling by taxicab (having controlled for land use, building volumes, and similar variables) despite the taxicab’s higher fares and ability to serve a wider range of origin-destination pairs. If this is the case, then the taxicab’s role as a transit substitute here outweighs its role as a complementary mode that fulfills demand the Red Line could not satisfy. The models I specify reveal the taxicab’s tendency to serve those same spatial and temporal concentrations of demand, while their residuals identify times and places where the relationships diverge from their normal patterns.

The dependent variable in the first set of models is the quantity of taxicab pickups per block group, averaged across the four weekdays in the sample.¹⁵ Each block group

¹⁵ The four weekdays are averaged, although separate models could be specified for each weekday to capture seasonal differences in taxicab activity. The decision to average the four days’ observations becomes necessary for the sake of simplicity, since four separate times of day are also modeled and variation by time of day is of greater interest than seasonality. Modeling taxicab activity for four different times of day in each season would require 16 different models, which would potentially obscure some of the relationships that are most relevant to this analysis.

therefore constitutes one observation, and the models use 544 observations in all. This unit of analysis allows the models to capture spatial variations in taxicab activity. Four separate models are specified using roughly the same independent variables, and these models correspond to four separate three-hour periods during the weekday in order to capture different demand patterns (2:00 to 5:00 a.m.; 6:00 to 9:00 a.m.; 4:00 to 7:00 p.m.; 8:00 to 11:00 p.m.). Thus, each model's dependent variable will be the number of taxicab pickups in a block group during a three-hour period.

In addition to the independent variables that describe characteristics of block groups and times of day, which I summarize below, the following indicators of transit access serve as independent variables in this model:

- **MBTA rail access:** Four separate variables represent block groups' proximity to the four principal MBTA rail lines (Red, Blue, Orange, and Green) using a function that approximates distance decay. Access to a given line is calculated using the shortest-path distance from a block group's centroid to the nearest station on that line, but the distance itself does not provide this variable's value. Instead, each rail access variable assumes a value of zero for block groups within a 0.5-mile distance of that line, and beyond that distance the variable's value increases by the natural logarithm of distance from the rail station. In other words, $x = 0$ when distance from transit d is less than 0.5 miles, and $x = \ln(d - 0.5)$ when d is greater than or equal to 0.5 miles. This achieves the purpose of treating block groups within the half-mile walking radius of a transit line uniformly while representing the rapid decline in one's willingness to walk to a transit station beyond that half-mile distance. The logarithmic increase in this variable's

value approximates the fact that longer walking distances become relatively undistinguishable from each other to a prospective transit rider.

- **MBTA Silver Line access:** A dummy variable represents the Silver Line in these models. If a census block group's centroid falls within a 0.5-mile straight-line distance of the Silver Line, that block group assumes a value of 1, and takes a value of 0 otherwise.
- **MBTA bus access:** Modeling each bus route's impact on taxicab trip generation would require an excessive number of variables. Therefore, the number of bus routes accessible from a given census block group at a given time serves as a proxy variable for bus access in this model. A bus route must intersect a block group to be considered accessible from that block group, and routes with multiple variants are considered as single routes. A second variable represents access to the 11 highest-ridership MBTA bus routes (as listed above) in the same manner. Again, the analytical approach I use for bus service is crude compared to the approach used for rail, but the complexity of Boston's bus route networks limits the precision with which I can isolate their impacts here.

Table IV-4 summarizes all independent variables and dependent variables included in the models I specify, including the transit access variables just described. The following list provides brief summary of the methods by which the remaining independent variables were generated:

- **Land area:** Total block group area minus water area within that block group (km²)
- **Open space:** Total open space within a block group, by land area (km²)
- **Open space %:** (Total open space) / (Total block group land area)

- **Commercial land use %:** $(\text{Total commercial land area}) / (\text{Total block group land area})$
- **Non-residential building volume:** Non-residential buildings are defined as all buildings within a block group whose footprints intersect a land use other than residential, as defined by MassGIS land use codes. Total building volumes for non-residential buildings are calculated by multiplying each building's footprint area by its height.
- **Zero-car household %:** The percentage of households within a block group that own zero cars, as given by the 2000 Census.
- **Population:** Total population residing in each block group, as given by the 2000 Census.
- **Population density:** $(\text{Total population}) / (\text{Total block group land area})$
- **Intersection density:** Using the GIS Network Analyst tool, Boston's street system is converted into a network with a node representing each intersection. The total number of nodes within each block group is normalized by the block group's land area to calculate intersection density.

Table IV-4: Summary of dependent and independent variables in taxicab activity models

			Mean	Median	Min.	Max.	St. Dev.	Expected Relationship		Year	Source
								Trip gen.	Transit subst.		
Dependent Variables	Taxicab Pickups per Block Group	AM Pk.	6.1	1.00	-	340	25.1			2010-2011	City of Boston
		PM Pk.	10.4	0.50	-	972	61.7				
		Eve.	9.8	0.50	-	696	48.8				
		Night	1.5	0.25	-	61	5.0				
	Transit Substitute Pickups per Block Group	AM Pk.	2.2	-	-	132	10.0			2010-2011	City of Boston
		PM Pk.	4.0	-	-	431	24.4				
		Eve.	4.1	-	-	306	21.0				
		Night	-	-	-	-	-				
	Transit Substitute Share by Block Group	AM Pk.	16%	0%	0%	100%	24%			2010-2011	City of Boston
		PM Pk.	16%	0%	0%	100%	26%				
		Eve.	17%	0%	0%	100%	27%				
		Night	0%	0%	0%	0%	0%				
Independent Variables	Land area (km ²)		0.2	0.1	0	5.8	0.4	+	0	N/A	N/A
	Open space (km ²)		0.0	0.0	0	2.3	0.2	-	0	1999	MIT Geodata
	Open space (%)		9%	2%	0%	143%	16%	0	-	1999	MIT Geodata
	Comm. LU (%)		13%	8%	0%	100%	16%	+	+	2005	MassGIS
	Non-res. bldg. vol. (10 ⁶ m ³)		0.6	0.2	0	18.3	1.5	+	-	2002	USGS
	Zero-car HH (%)		33%	31%	0%	88%	18%	+	+	2000	U.S. Census
	Population (1,000)		1.1	1.0	0	4.1	0.5	+	0	2000	U.S. Census
	Pop. dens. (1,000 per km ²)		9.3	7.6	0	52.1	7.1	0	-	2000	U.S. Census
	Bus routes		4.3	3.0	0	26.0	4.5	-	+	2007	MBTA
	Major bus routes		1.2	1.0	0	7.0	1.5	-	-	2007	MBTA
	Blue Line dist. (log)		8.0	8.6	0	9.6	2.0	+	-	2006	MBTA
	Green Line dist. (log)		6.2	7.7	0	9.2	3.3	+	-	2006	MBTA
	Red Line dist. (log)		6.7	7.5	0	9.1	2.4	+	-	2006	MBTA
	Orange Line dist. (log)		6.5	7.7	0	8.8	2.7	+	-	2006	MBTA
	Silver Line (dummy)		0.1	0.0	0	1.0	0.3	-	+	2006	MBTA
	Int. density (100 per km ²)		1.5	1.3	0	6.6	0.8	-	-	2007	MIT Geodata
	Class 1 road (dummy)		0.1	0.0	0	1.0	0.4	+	+	2007	MIT Geodata
	Class 2-4 road (km)		0.7	0.3	0	16.8	1.4	+	+	2007	MIT Geodata
	Dist. from center (km)		6.2	5.9	0	15.3	3.4	-	-	N/A	N/A
	Med. HH income (\$10,000)		4.2	3.9	0.2	11.3	1.9	+	+	2000	U.S. Census
Airport dummy		0.0	0.0	0	1.0	0.0	+	0	N/A	N/A	

KEY	
+	Positive relationship expected
-	Negative relationship expected
0	No relationship expected

- **Class 1 road (dummy):** Any block group intersected by a Class 1 road (limited access highway) has a value of 1; any block group that does not has a value of 0.
- **Class 2-4 road:** Total kilometers of Class 2, 3, and 4 roadways within a block group (comprising most major roads) are added together to calculate this variable's value.
- **Distance from center:** Straight-line distance (km) from Boston's City Hall Plaza (an arbitrarily-defined center) to a block group's centroid, the location of which is calculated using GIS.
- **Median household income:** A block group's median household income, as given by the 2000 Census.
- **Airport dummy:** A dummy variable that has a value of 1 for block group 106955, which is coterminous with Logan Airport (see above) and assumes a value of 0 for all other block groups

Section B of the Appendix includes a correlation matrix of all dependent variables just listed. In general, few have strong positive or negative correlations with one another, but several do. Awareness of these correlations is necessary for the proper interpretation of model results in Chapter Five.

I model taxicab trip counts using Poisson regression, which treats an independent variable y as a function of $e^{\theta x}$. The Poisson regression method is commonly used to specify count models: A Poisson process, in which observed events occur independently of one another in continuous time, offers a reasonable approximation of taxicab trip generation by block group in Boston. The trip counts that a Poisson process generates fit a Poisson distribution, which reflects the probability of a certain number of events (such as taxicab pickups) occurring within a fixed time period and requires the

assumption that those events occur independently of one another at a certain average rate. These assumptions are appropriate for taxicab trip generation, in which individual taxicab pickups are not coordinated with one another and occur at average rates that appear fairly consistent over time. The aforementioned Poisson regression is the best modeling approach for observations generated by a Poisson process, and it yields coefficients that are linearly related to the natural logarithms of trip counts. In the next chapter, I interpret the results of the taxicab trip generation models I specify and discuss the significance of the coefficients for these Poisson regression models in greater detail.

If the trip count models indicate that taxicab pickups occur more frequently in areas that enjoy better transit access, this does not necessarily mean that those taxicabs are acting as substitutes for transit. A block group near an MBTA station, for example, may generate many taxicab trips to destinations that the Orange Line does not serve directly, thus complementing the mobility it provides. To the extent that this occurs in transit-accessible locations, the taxicab is still filling gaps in Boston's transit network. If a large share of these trips consists of transit substitutes, however, the taxicab and transit are simply transporting shares of the same travel demand. The complementary role aligns more closely with the taxicab's optimal purpose, as defined earlier in this thesis. Of course, transit access both reflects and reinforces many of the greatest concentrations of travel demand within a city, so we should not be surprised that the taxicab serves some portion of travel demand that mass transit could also potentially carry.

Model 2: The second set of models assesses the relationship between a block group's transit access and the percentage of its taxicab trips that do, in fact, substitute for transit service. Obviously, transit access is necessary for any taxicab trips to substitute for transit, but controlling for this and other factors should reveal the nuanced relationships

between the two modes. These models also use block groups as the unit by which the dependent variable is averaged, as well as the same three-hour time periods (although the 2:00 a.m. to 5:00 a.m. period is omitted here because it is outside of transit's service span, so substitution is impossible and every observation's value will be zero or close to zero).

Unlike the first set of models, the second set relies upon linear regression. While Poisson regression is appropriate for modeling trip counts, that approach is not suitable for modeling transit substitution shares by block group, which are distributed more normally. Instead of simply using the ordinary least squares (OLS) method of estimating the second set of models, however, I use Tobit regression. The standard Tobit model is used "for situations in which y is observed for values greater than zero but is not observed (that is, is censored) for values of zero or less" (Sigelman and Zeng 1999, 167). Transit substitution share—the y variable in this second set of models—fits this description, as it cannot have a value other than zero (by definition) for trips that do not begin and end within transit's service area. The Tobit approach accounts for the effect of censoring by modeling a latent dependent variable as a linear function of independent variables and allowing the latent variable to assume negative values as well as positive values. When the latent dependent variable is positive, however, it represents the observed variable (transit substitution share, in this case). Many of the independent variables used in the first set of models will reappear here, as many characteristics of urban places (including transit access indicators) are expected to have significant relationships with taxicab trip generation as well as transit substitution.

The final question for which these two sets of models prepare the way is also the most difficult to answer: Which parts of Boston are underserved by the taxicab, in light of the

public transportation role that has been defined for the mode? As this chapter repeatedly emphasizes, realized demand is an insufficient indicator of unmet demand; however, the residuals of the models specified provide an imperfect means of inferring the presence of unmet demand throughout Boston. If a model predicts much higher levels of trip generation for a block group than are actually observed, that low taxicab activity may be explained by a lack of taxicab service rather than a lack of demand. Clues from the model results will facilitate inferences of this kind that merit further investigation, and this thesis does not attempt to answer this final question with certainty, although it affirms the value of future research on the subject.

Gaining greater insight into the taxicab's relationship to other forms of public transportation yields valuable conclusions about how likely a neighborhood is to generate taxicab activity. If median household income displays a strong positive correlation with taxicab pickups, we might logically infer that low trip generation occurs due to lack of demand. If centrality of location exerts the largest influence after other factors have been controlled for, we might infer the existence of demand in outlying neighborhoods that supply does not effectively reach. Finally, the degree to which taxicabs act as transit substitutes or complements will indicate the likelihood that choice riders will receive better or worse taxicab service than captive riders, all else being equal. The next section delves into this question more deeply after presenting the results of the analysis that this chapter has described.

V. RESULTS AND INTERPRETATION

Following the prior chapter's description of the research methodology this thesis employs, the current chapter summarizes and interprets the results of that analysis. This summary proceeds through the three phases that structure the investigation, with new conclusions about Boston's taxicab system drawn from each phase. The first phase serves a primarily descriptive purpose, establishing familiarity with Boston's taxicab activity patterns in preparation for the subsequent phases' analysis. The second phase introduces the distinction between taxicab trips that act as transit substitutes or complements, outlining the criteria by which to classify trips as one or the other and then applying this classification criteria to the four-day sample of Boston taxicab trips. The third phase approaches the research questions this thesis has set out to answer: Which factors influence the taxicab's relationship to mass transit and the degree to which it complements Boston's mass transit system? Two sets of regression models provide a lens through which to examine this relationship. The final section of this third phase attempts to infer which parts of Boston, if any, are underserved by the taxicab as well as mass transit.

A. Phase One: General taxicab activity patterns in Boston

The previous chapter described numerous metrics that provide a basic understanding of taxicab activity in Boston, explaining the relationships between those variables and taxicab supply as well as demand. Understanding the relationship between a location's transit access and its taxicab service, after all, requires an understanding of when and where taxicab activity actually occurs. Examining this distribution raises more questions

than it answers, however, and the insight this examination yields largely reinforces the long-held intuitive knowledge of taxicab operators and passengers regarding when and where taxicab supply meets demand. Observed variations in taxicab fares, trip distances, and origin-destination pairs add nuance to this initial portrait but still fail to demonstrate how taxicabs and transit truly interact. Nonetheless, the analysis that follows must build upon the base introduced in this first phase, because realized taxicab demand is an important indicator of the relationships between transit access and taxicab service.

TAXICAB PICKUPS AND DROP-OFFS

The spatial and temporal distributions of individual pickups and drop-offs by Boston taxicabs are among the most basic and predictable metrics of taxicab service. Total taxicab activity levels vary somewhat across the four sample days (Table V-1). The highest volume of taxicab activity occurs in May, with more than 37,000 trips during a 24-hour period, while the lowest volume of activity occurs in August, with about 33,000 trips during that sample day.

Table V-1: Total daily taxicab trips in Boston

		Total Trips
May 12	2010	37,441
Aug 4	2010	33,233
Oct 20	2010	34,953
Jan 26	2011	34,161
Average		34,947

Figure V-1 maps all taxicab pickups and drop-offs throughout each of the four 24-hour periods from the study sample, and a cursory glance at the four pairs of maps suggests seasonal consistency in the spatial patterns of taxicab pickups and drop-offs.

Figure V-2 and Figure V-3 show the average spatial distribution of Boston’s daily taxicab pickups and drop-offs throughout the year, aggregated by census block group and normalized by block group land area, illustrating these trends more generally.

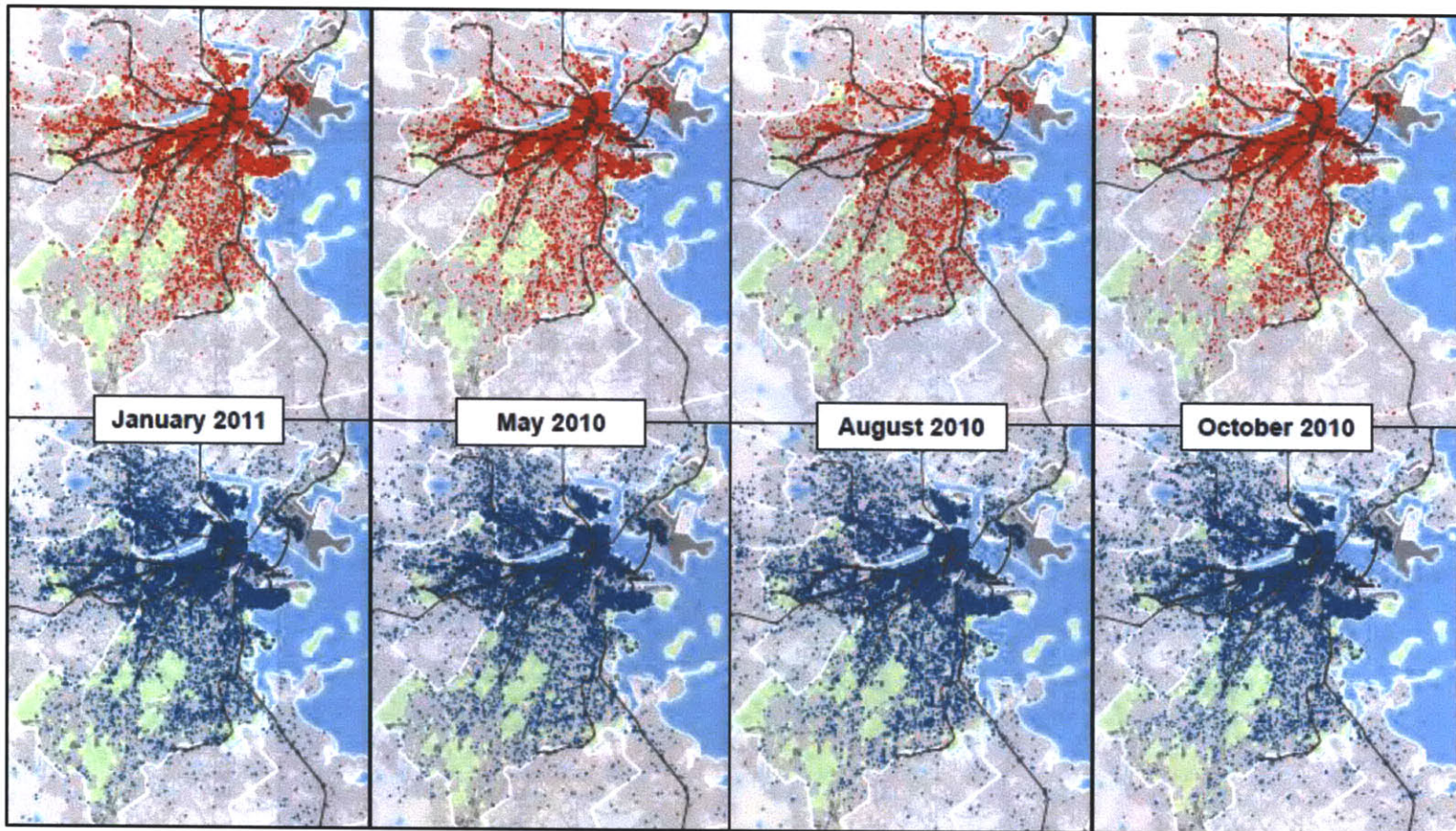


Figure V-1: Daily taxicab pickup and drop-off locations in Boston

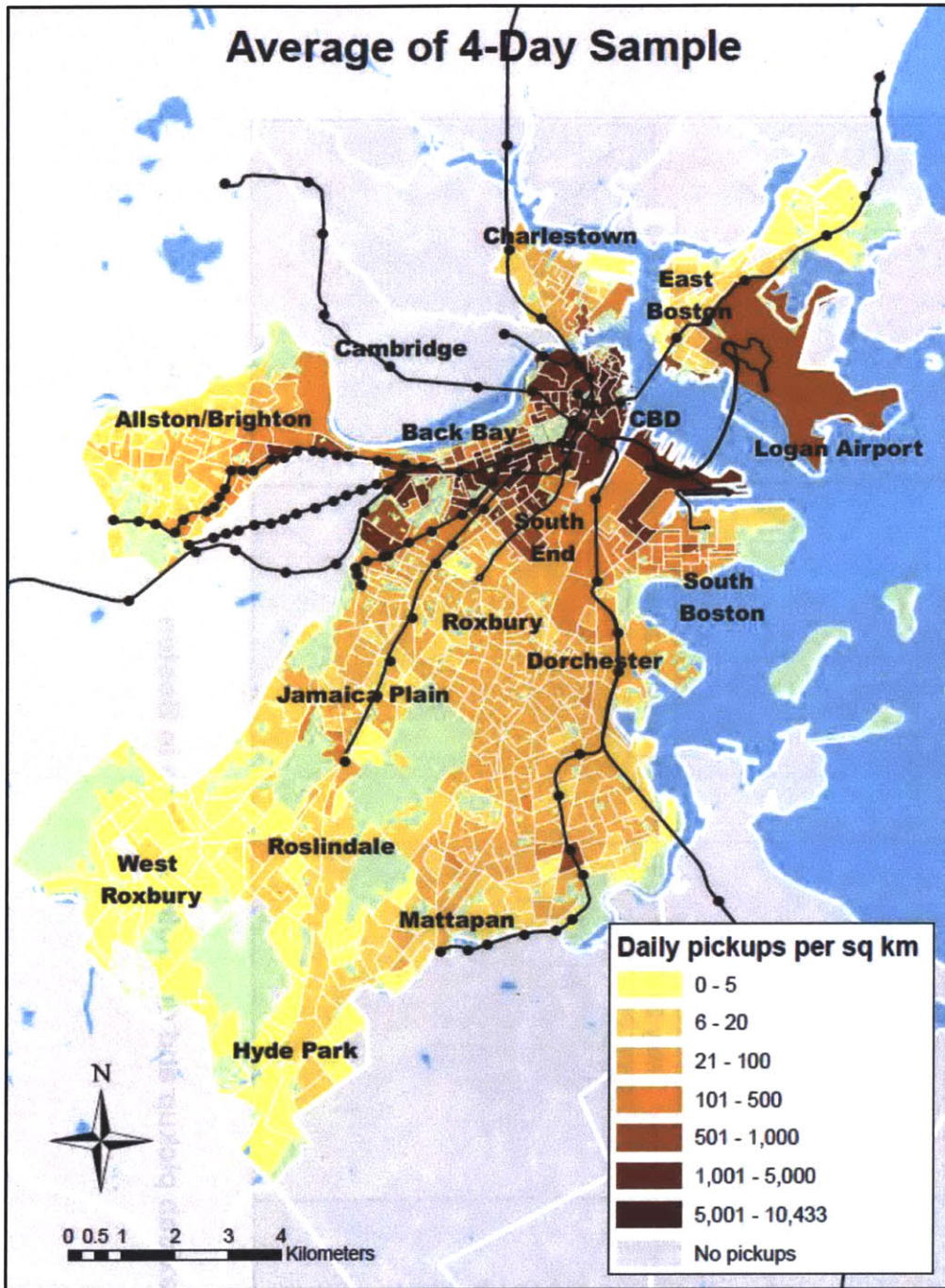


Figure V-2: Daily taxicab pickup density by census block group

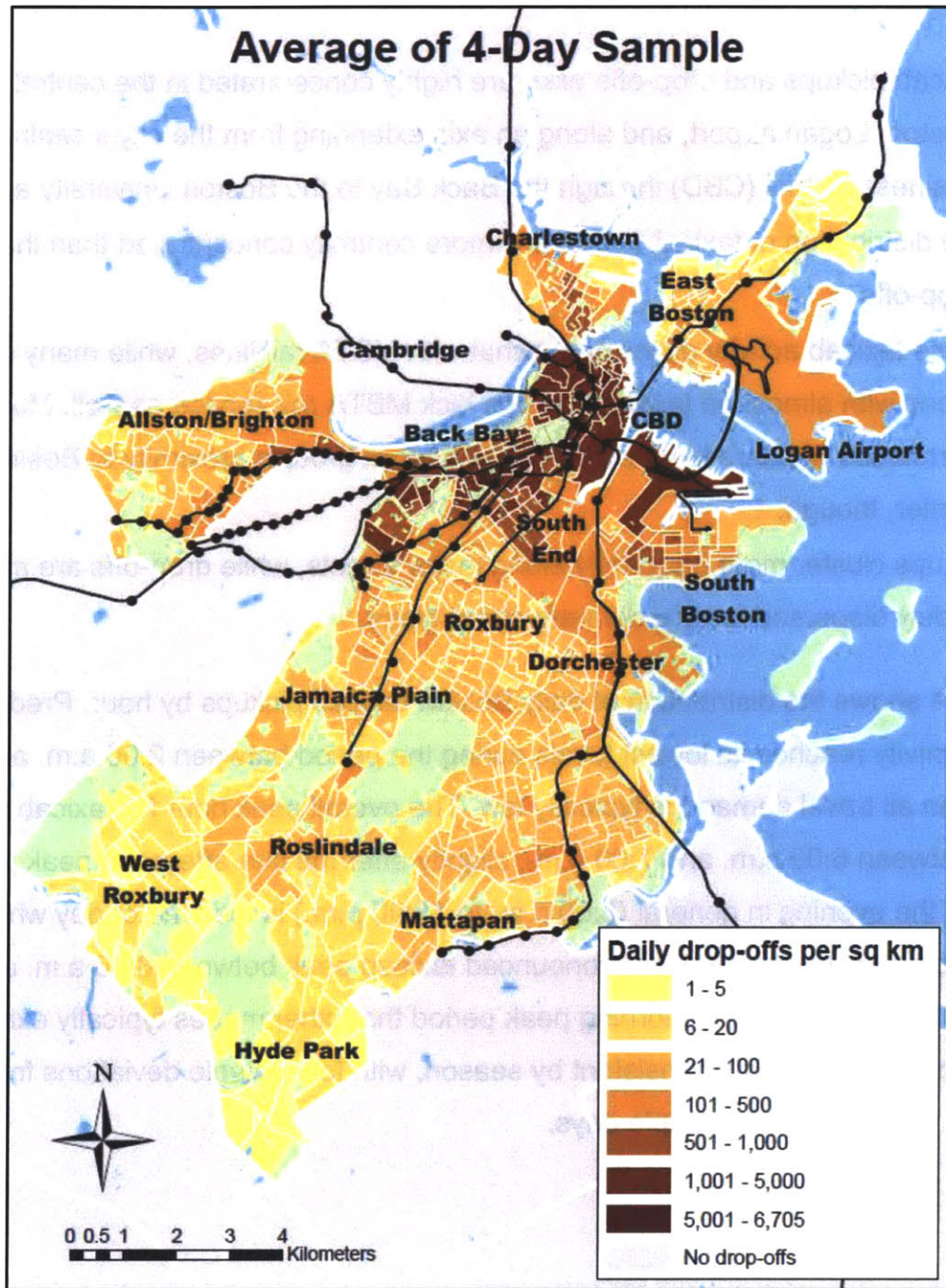


Figure V-3: Daily taxicab drop-off density by census block group

Several conclusions emerge from the data on taxicab pickups and drop-offs:

- Taxicab pickups and drop-offs alike are highly concentrated in the central part of Boston, Logan airport, and along an axis extending from the city's central business district (CBD) through the Back Bay to the Boston University area.
- The distribution of taxicab pickups is more centrally concentrated than that of drop-offs.
- Dense taxicab activity aligns somewhat with MBTA rail lines, while many of the areas with almost no taxicab pickups lack MBTA rail service as well. Much of this correlation appears to be a function of a block group's proximity to Boston's center, though.
- Pickups cluster more frequently along major streets, while drop-offs are more widely dispersed among different street types.

Figure V-4 shows the distribution of daily Boston taxicab pickups by hour. Predictably, taxicab activity reaches its lowest levels during the period between 2:00 a.m. and 6:00 a.m., when all travel demand is typically low. The overall peak hour for taxicab activity occurs between 6:00 p.m. and 7:00 p.m., slightly after the late afternoon peak for work trips, and the evening in general (5:00 p.m. to 11:00 p.m.) is the time of day when taxicab activity is highest. A less pronounced taxicab peak between 8:00 a.m. and 9:00 a.m. also coincides with the morning peak period that other modes typically exhibit. All of these patterns are fairly consistent by season, with few notable deviations from hourly averages across the four sample days.

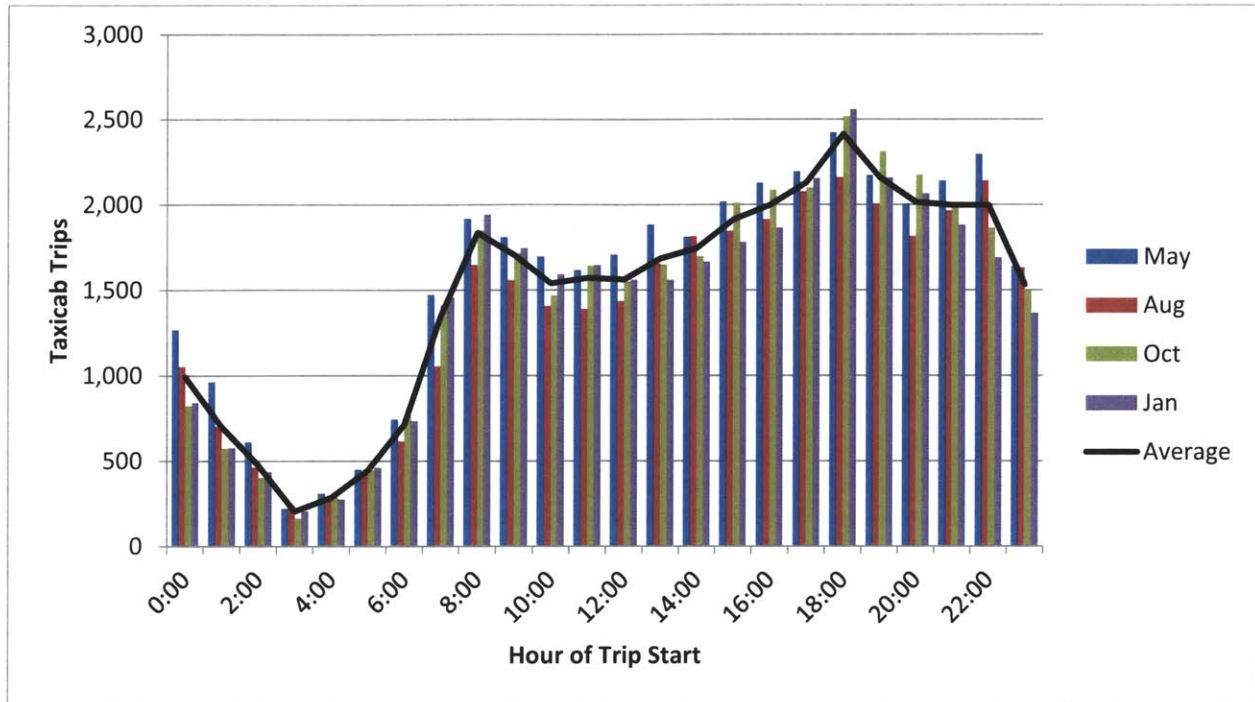


Figure V-4: Boston taxicab trips per hour (weekday)

TRIP DISTANCES AND DURATIONS

Beyond the spatial variations in taxicab pickups and drop-offs throughout Boston, the characteristics of these trips also vary by time and place. The average distances and durations of taxicab trips offer important clues about the types of mobility that taxicab users desire in different locations. Figure V-5 and Figure V-6 map average trip distances and durations by block group of trip origin, revealing an overall average trip distance of 2.8 miles and an average trip duration of 11.7 minutes. In general, the longest trips by distance and time occur at the airport and on Boston’s

periphery, especially in Allston, Columbia Point peninsula, and the far southern part of the city. The

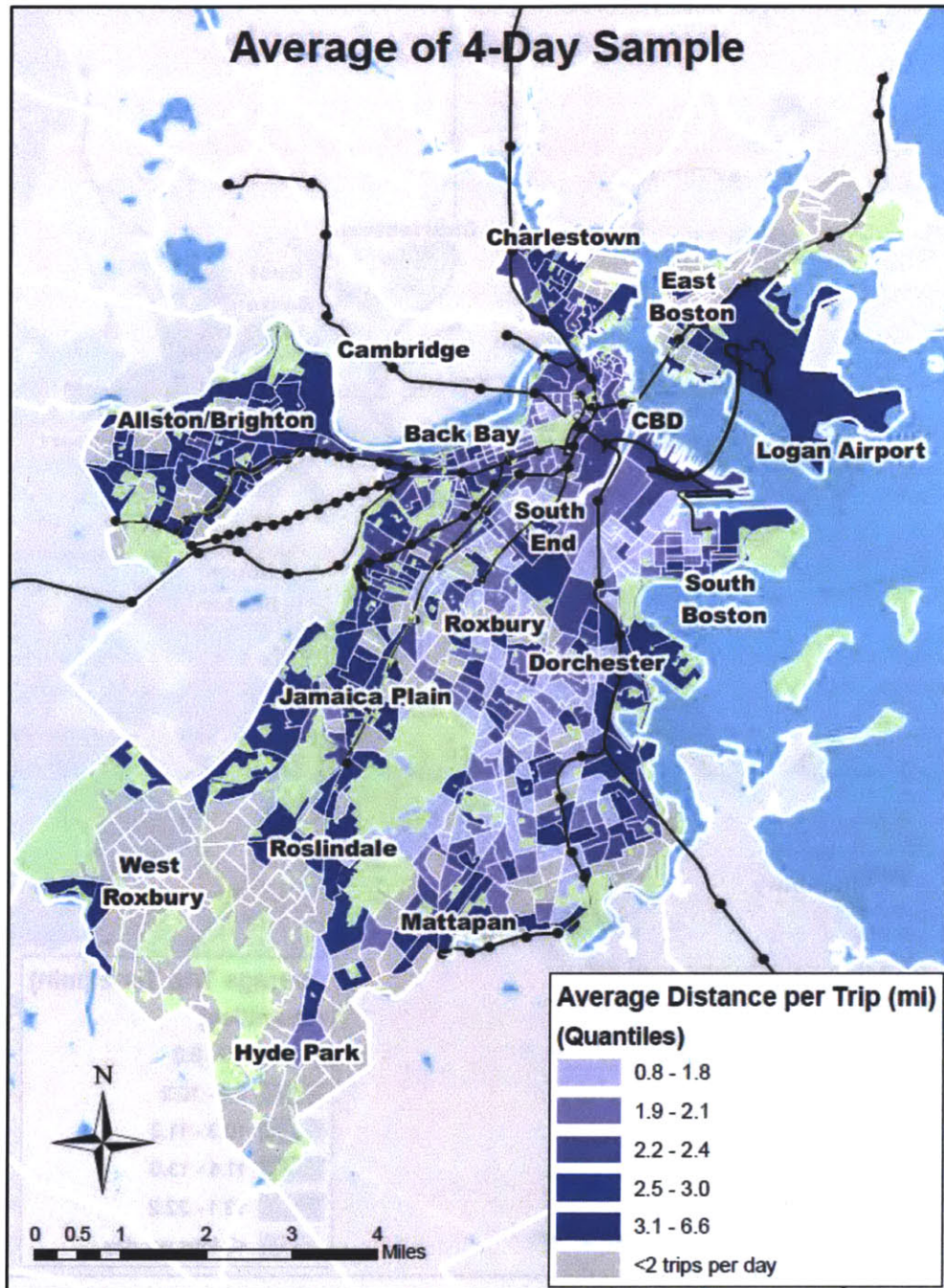


Figure V-5: Average taxicab trip distance by pickup location

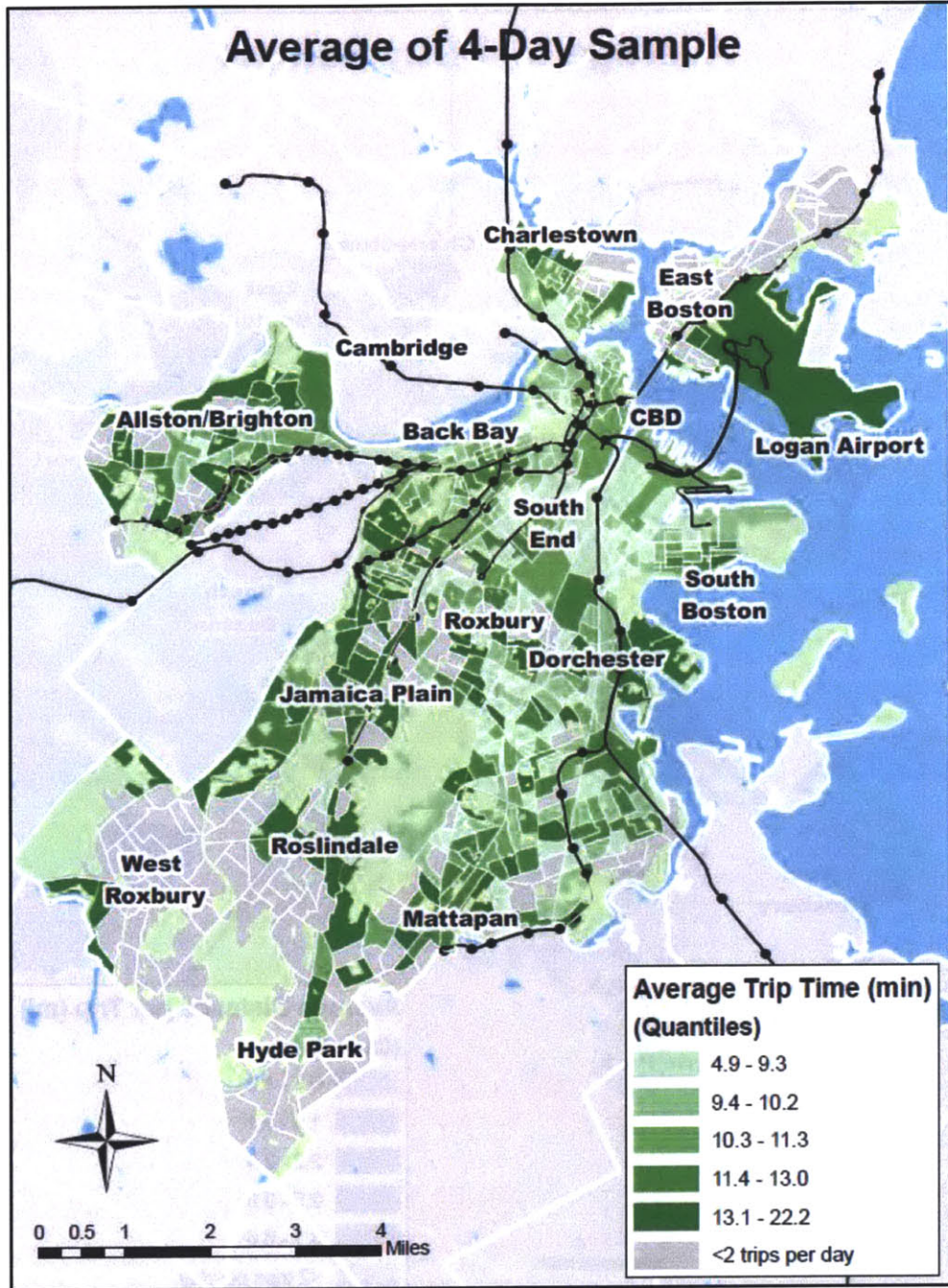


Figure V-6: Average taxicab trip duration by pickup location

shortest-distance trips occur closer to Boston's center, but these are not the shortest trips by time, probably due to greater congestion and slower vehicle speeds. Additional pockets of short trips are observed in Dorchester and Roxbury, in the area between the Orange Line and the Red Line.

As the prior chapter explains, travel time is an important component of a trip's generalized cost, while taxicab trips' distances directly determine their fares. Trip lengths may vary by location for a variety of reasons: higher density that creates better access to a range of destinations; better or worse service levels from alternative modes; or user preferences and willingness to pay that vary by location. All three factors likely account for the variance in Boston's taxicab trip lengths. Certain parts of Boston also fulfill specialized purposes that result in longer trips: Logan Airport, for example, is a source of travel demand for destinations well beyond Boston itself, and taxicabs serve many of these trips. No correlation between average taxicab trip length and proximity to MBTA rail stations is evident from these maps, although slightly longer trips appear to originate near certain stations.

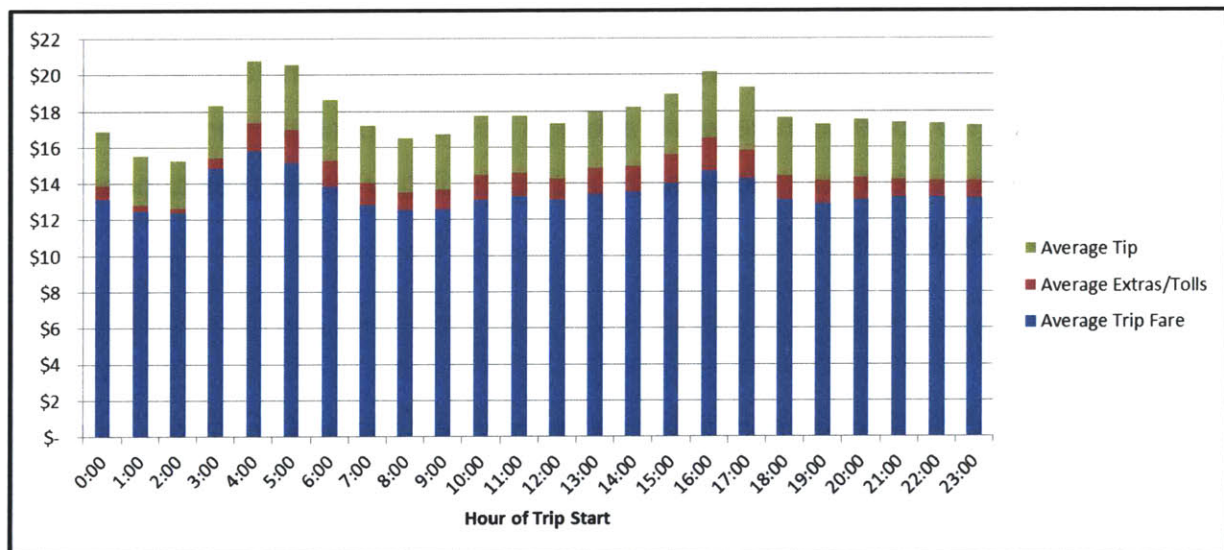
TAXICAB FARES

Taxicab fares are a critical component of taxicab supply and demand in any city, and Boston is no exception. While travel time is an important component of any trip's generalized cost, monetary prices are equally important and much more tangible. As with trip times and distances, then, average fares of realized trips will vary by location due to alternative modes' availability, the proximity of desired destinations, and users' willingness to pay. Taxicab fares are closely correlated with trip distances, as Boston's fare rates are determined directly by trip mileage (\$2.60 for the first 1/7 mile and \$0.40 for each subsequent 1/7 mile). Nevertheless, total fares do not vary precisely by

distance: Tolls, tips, and any other extra charges all introduce variability to the relationship between trip distances and trip fares.

For all Boston taxicab trips in this sample, the average base fare is \$13.33, while the average tip is \$3.20¹⁶ and the average total fare (including tips as well as tolls and extras) is \$17.77. Figure V-7 shows average trip fares by time of day (excluding tolls, extras, and tips), while Figure V-8 displays average taxicab trip fares by block group of trip origin. Both reflect patterns quite similar to those of trip distances and durations, although the correlation is not perfect: The highest fares occur for taxicab pickups at

Figure V-7: Average taxicab trip fares by hour



¹⁶ Tips are only recorded when a taxicab passenger pays by credit card. As a result, this average tip estimate is almost certainly biased upward, because the data shows that trips in which passengers pay by credit card have higher average fares than trips in which passengers pay with cash.

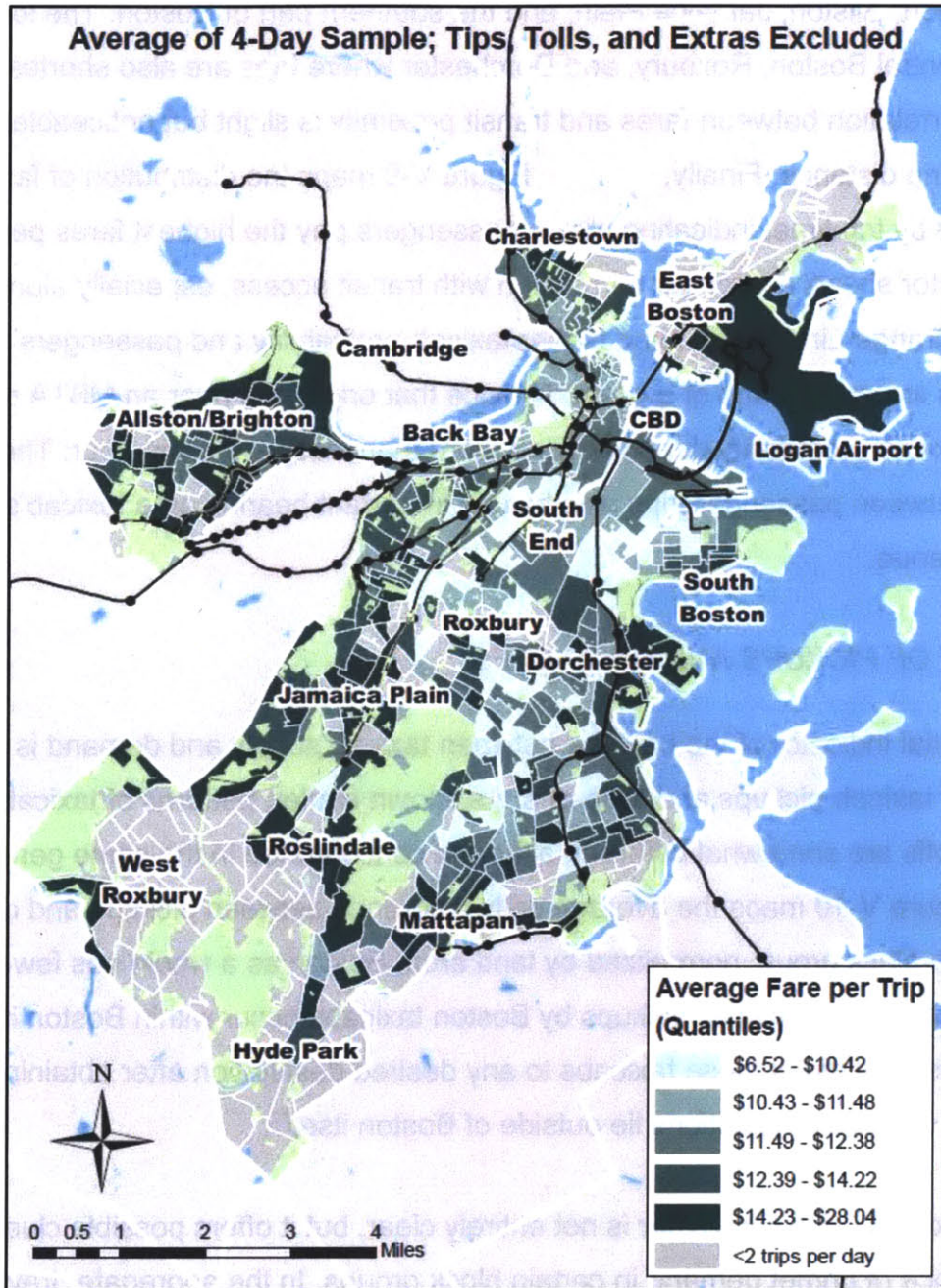


Figure V-8: Average taxicab trip fare by pickup location

Logan Airport, Allston, Jamaica Plain, and the southern part of Boston. The lowest fares occur in central Boston, Roxbury, and Dorchester where trips are also shortest. The positive correlation between fares and transit proximity is slight but noticeable, as is the case with trip distance. Finally, Figure V-9 maps the distribution of fares normalized by trip time, indicating where passengers pay the highest fares per trip hour. This indicator shows a stronger correlation with transit access, especially along the Red Line and Orange Line, suggesting higher taxicab profitability and passengers' higher willingness to pay for a trip of a given distance that originates near an MBTA station. Of course, taxicab profitability depends upon more than income per trip hour: The time that elapses between passenger trips also has an important bearing on a taxicab's overall rate of revenue.

BALANCE OF PICKUPS AND DROP-OFFS

One potential indicator of the balance between taxicab supply and demand is the spatial balance of taxicab pickups and drop-offs. As shown earlier, patterns of taxicab pickups and drop-offs are somewhat different, although concentrated in the same general places. Figure V-10 maps the average daily difference between pickups and drop-offs within each block group, normalized by land area. Boston as a whole has fewer drop-offs than pickups: Almost all pickups by Boston taxicabs occur within Boston itself, while passengers may direct these taxicabs to any desired destination after obtaining service and many of these destinations lie outside of Boston itself.

The significance of this indicator is not entirely clear, but it offers possible clues about the existence of unmet demand in certain block groups. In the aggregate, travel demand should be more or less directionally balanced, as a one-way trip generally makes up one half of an eventual round trip. Locations where taxicab pickups greatly exceed drop-

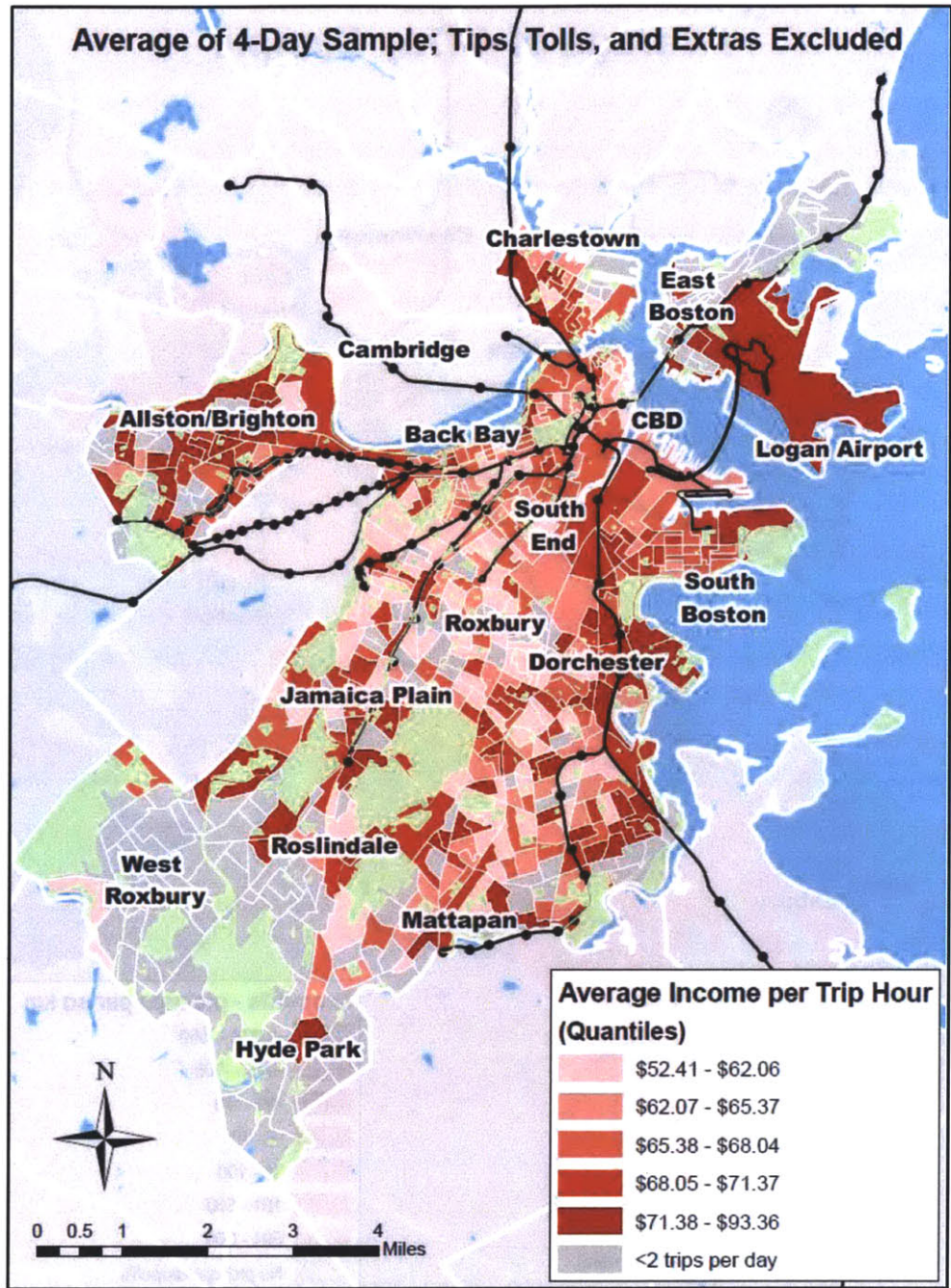


Figure V-9: Average income per taxicab trip hour by pickup location

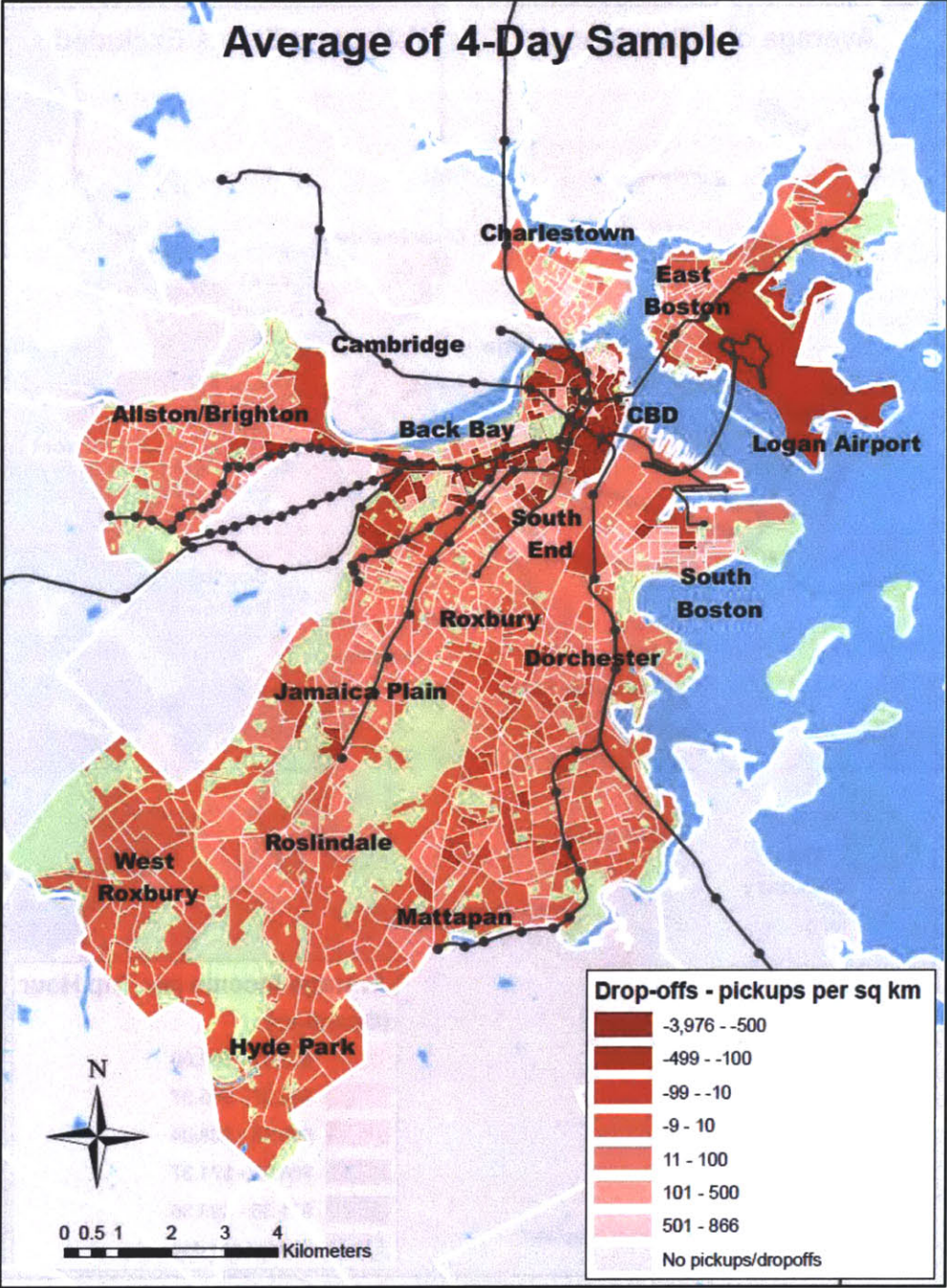


Figure V-10: Pickup/drop-off balance by census block group

offs, such as Boston's CBD, raise the question of which mode fulfills travel in the opposite direction (in this case, trips toward the center of the city). Other municipalities' taxicabs undoubtedly account for some of these trips' other halves (especially in block groups near Boston's border), but those taxicabs probably do not make up for the drastic imbalances observed in certain areas.

Another plausible explanation is that many inbound trips use a different mode than the taxicab. Areas with many more pickups than drop-offs enjoy high taxicab service levels that encourage the use of the taxicab as a mode due to lower waiting times for service (and therefore lower generalized travel costs). In places where pickups greatly exceed drop-offs, taxicabs are more likely to return to these areas after dropping passengers off elsewhere due to the demand that exists in these locations. In areas with many more drop-offs than pickups, conversely, passengers reveal the same round-trip demand but perhaps do not choose the taxicab for the outbound trip due to the wait times associated with obtaining taxicab service there. In particular, Columbia Point peninsula, Charlestown, and areas surrounding high-pickup areas in central Boston display this negative balance. For these districts, concentrations of travel demand with few cruising taxicabs (or passengers walking to a nearby census block where cruising taxicabs are easier to hail) may explain their imbalance. Interestingly, areas near MBTA stations have many more pickups than drop-offs in central Boston, while the reverse is somewhat true farther from the center. This could, in fact, support the above hypothesis about taxicabs and transit: If outbound trips that end near MBTA stations (transit substitute trips) occur by taxicab much more frequently than their inbound counterparts, pickups should exceed drop-offs in central Boston and the reverse should be true on the periphery.

SUMMARY OF PHASE ONE

The preceding display of taxicab service characteristics in Boston provides an interesting if limited introduction to the relationship between taxicabs and mass transit. Maps of the various characteristics of taxicab trips reveal larger-scale spatial patterns, but visualizing the spatial and temporal variations of taxicab activity simultaneously is difficult and deeper analysis is necessary to understand the true nature of these patterns. A few general conclusions from this first phase inform the subsequent analysis:

- By almost any of the above indicators, taxicab service varies throughout Boston, and the visible correlations among many of these indicators suggest distinct differences in how passengers use taxicabs throughout the city. In particular, taxicab activity is much greater in downtown Boston and at Logan Airport than in the outlying residential areas of the city, while trips from the airport and the city's periphery tend to be longer.
- The patterns on display only reflect realized taxicab demand, while unmet demand remains invisible. Average fares do provide clues about willingness to pay for travel, especially when viewed through the lens of transit access, and trip distribution maps illustrate the vast concentration of taxicab activity in certain locations. These data enable hypotheses about which parts of Boston might benefit least from the mobility that taxicabs provide.
- Measures of taxicab service levels, from trip counts to average fares, exhibit clear correlations with spatial characteristics that influence supply and demand (and thus realized demand). Only by controlling for variables like centrality, commercial activity, or street configuration can we isolate the relationship

between the taxicab and mass transit in order to understand each mode's public transportation role in Boston.

B. Phase Two: Taxicab trips as transit substitutes and complements

Moving from merely describing the activity of Boston's taxicabs to understanding how the taxicab acts as a complement to or substitute for mass transit requires the intermediate step of determining which taxicab trips are transit complements and which are substitutes. In order for transit to present a viable alternative to taxicab travel, it must connect a trip's origin to its destination within a reasonable travel time during the service span of the transit alternative.

Certain trip types exhibit additional characteristics that make transit a less likely alternative for the mobility they provide. In this study, airport trips and short-distance trips are the two principal trip types that are ruled out as transit substitutes, for reasons the discussed in Chapter Four. That chapter also describes in greater detail the specific criteria used to classify taxicab trips in this analysis and the assumptions that classification scheme requires.

At the individual trip level, the characteristics of passengers themselves, including willingness to pay for travel and preferences for certain modes, influence the true substitutability of taxicabs and transit; however, this thesis primarily concerns itself with the mobility that taxicabs enable rather than which types of people choose to use that mobility. In other words, a high volume of taxicab trips that duplicate transit routes do not represent a problem if places in Boston with fewer public transportation options also benefit from the mobility that taxicabs provide.

TRIP CATEGORIZATION

Table V-2 provides a detailed breakdown of the daily trip counts classified as substitutes for each MBTA line, using the service area definitions that Chapter Four explains. This table also tallies the total daily trips that act as substitutes for the 11 major MBTA bus routes listed in Chapter Four (the trip categories of rail and bus substitute overlap). In addition, the table provides totals for airport trips and short trips, the two categories excluded from consideration as transit substitutes. Finally, Figure V-11 maps the distributions of transit substitutes and complements by pickup location, while Figure V-12 displays transit substitute trips as a percentage of total taxicab trips by time of day.

Table V-2: Trip categories as percentages of total trips

	Transit substitutes							Other Groups		
	Blue Line	Orange Line	Red Line	Green Line	Silver Line	Any Rail	Bus	Any Transit	Airport Trip	Short Distance (Walking Sub.)
May 12 2010	1.9%	10.2%	4.1%	23.5%	11.3%	33.6%	3.0%	34.4%	20.1%	5.3%
Aug 4 2010	2.1%	10.2%	4.0%	24.2%	10.5%	33.7%	3.2%	34.6%	20.1%	6.4%
Oct 20 2010	1.9%	11.0%	4.1%	24.5%	10.8%	34.2%	3.6%	35.1%	25.7%	5.0%
Jan 26 2011	2.6%	12.3%	4.9%	25.4%	13.7%	38.1%	4.3%	39.4%	15.5%	6.7%
Average	2.1%	10.9%	4.3%	24.4%	11.6%	34.9%	3.5%	35.9%	20.3%	5.9%

SUMMARY OF PHASE TWO

The aggregate occurrence of transit substitution as a share of total taxicab activity is relatively consistent, as this section has shown. These distributions of transit substitutes and complements provide a transition to the third and final phase of this analysis. By definition, taxicab trips in the transit substitute category must begin and end near a rail

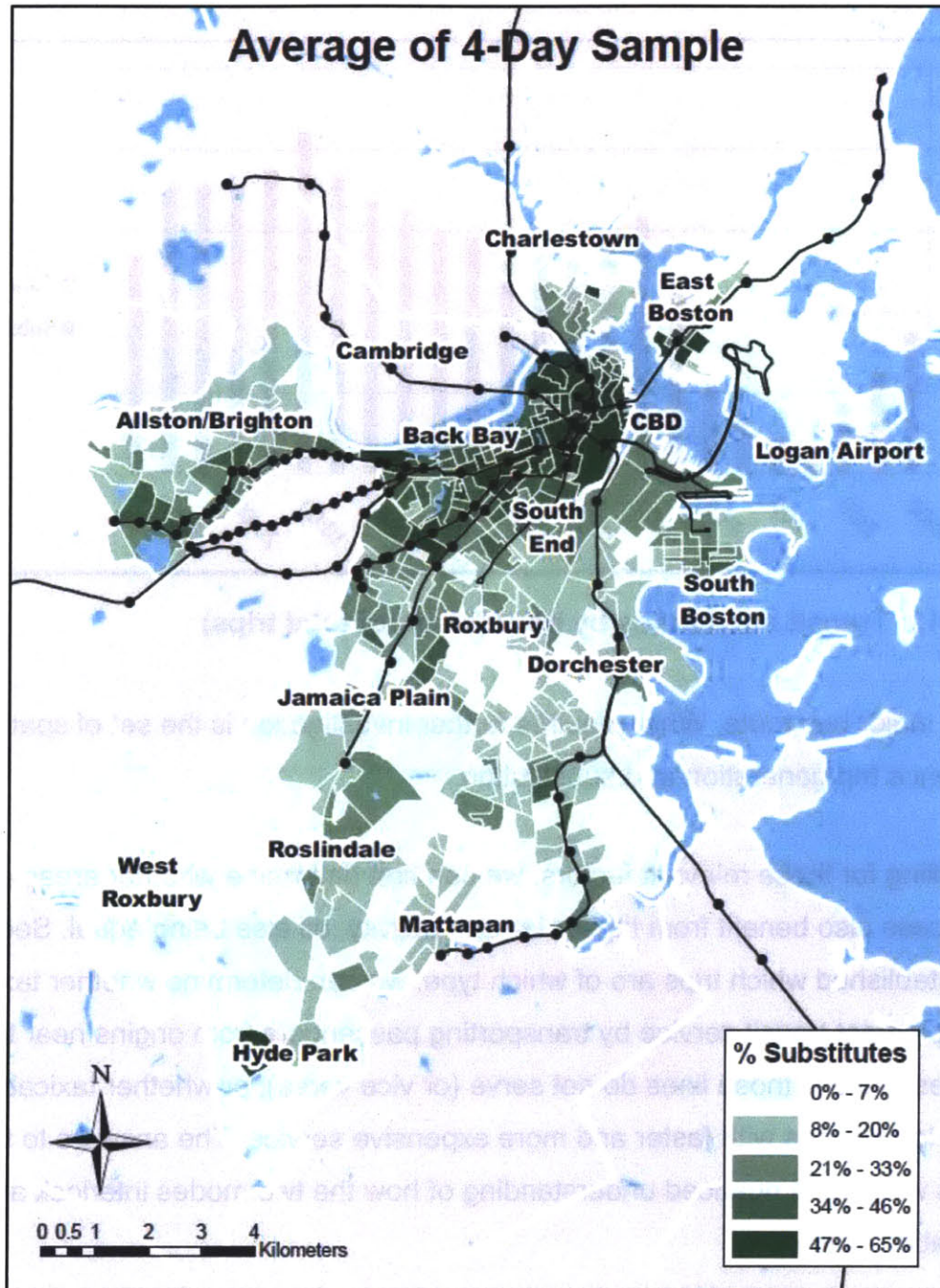


Figure V-11: Transit substitution (% of total daily trips by block group)

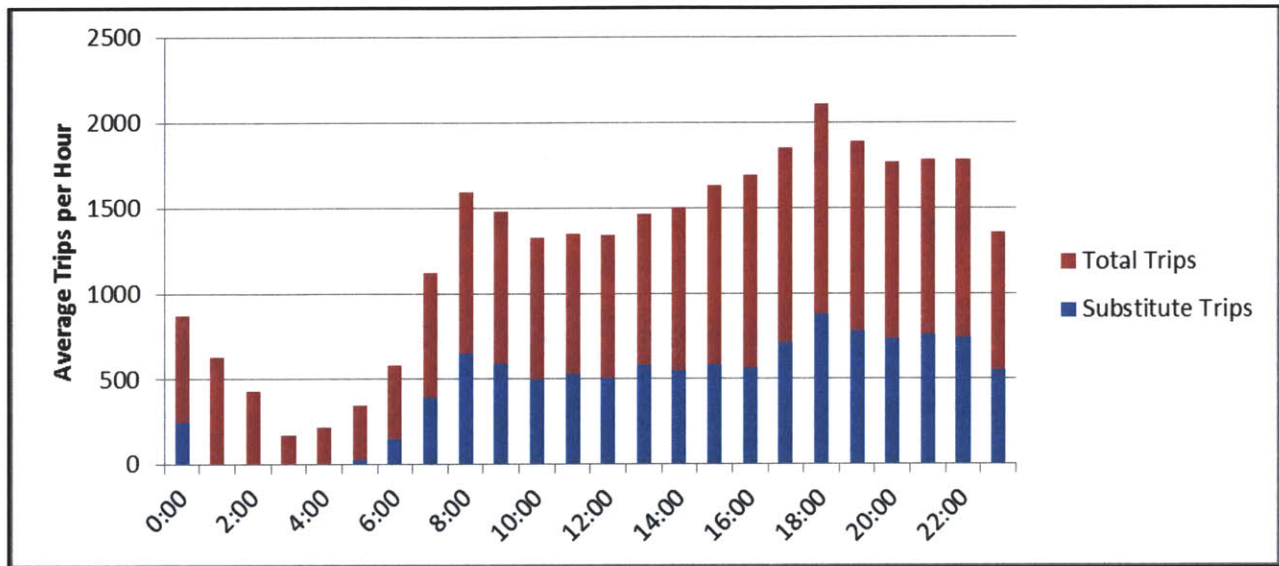


Figure V-12: Transit substitutes by hour (share of total trips)

station or major bus route. What requires further investigation is the set of spatial factors that influence trip generation and substitution.

By controlling for these relevant factors, we can first determine whether areas with good transit access also benefit from higher taxicab activity, all else being equal. Second, having established which trips are of which type, we can determine whether taxicabs truly complement transit service by transporting passengers from origins near transit lines to destinations those lines do not serve (or vice versa), or whether taxicabs simply duplicate transit lines with faster and more expensive service. The answers to these two questions will yield a nuanced understanding of how the two modes interlock as a public transportation system.

C. Phase Three: Regression models of taxicab activity

The analysis thus far has described Boston's general taxicab activity, as observed, and sorted that activity into categories based upon its relationship to the city's mass transit service. The current phase synthesizes the information gained from the preceding steps by identifying specific factors that exhibit significant associations with taxicab trip generation in Boston. This thesis has argued so far that certain aspects of a place directly influence the travel demand concentrated there, and that other characteristics determine its desirability for taxicabs trying to operate profitably. The literature I have reviewed and the data I have presented to this point inform reasonable hypotheses about which spatial characteristics are most relevant to taxicab trip generation. Testing these hypotheses reveals which factors are most strongly correlated with taxicab pickups, all else being equal, and regression analysis enables controlling for certain factors to isolate the specific relationships between taxicab activity and each factor. Some of these relationships may be causal, although regression modeling cannot prove the existence of causality.

As restated frequently throughout this thesis, the primary question I ask about taxicab distribution is whether transit access typically corresponds to better or worse taxicab activity, and whether that activity tends to duplicate transit service. Because realized demand is an insufficient indication of total demand, isolating the most important determinants of realized demand facilitates inferences about which areas have more or less taxicab service than expected, based on their characteristics. Certain areas may be quite likely to demand taxicab service, but show little realized demand because they receive poor taxicab service levels.

The two sets of regression models I specify here address my central questions directly. The first, a Poisson model, regresses taxicab pickup counts by census block group against a variety of independent variables (described in the previous chapter) during four separate three-hour periods of the day. Since I have established the goal of understanding relationships between the taxicab system and mass transit, indicators of transit access are critical independent variables in these models: the shortest-path distances between each census block group's centroid and the nearest station of each major MBTA subway line (Red, Blue, Green, and Orange); a dummy variable for whether the census block group falls within a 0.5-mile straight-line buffer of the Silver Line; and the number of MBTA bus routes that intersect each block group. The relationships between each of these variables and taxicab trip counts, with other spatial variables controlled for, will partially indicate whether transit-accessible places have concentrations of the kinds of travel demand that taxicabs also tend to serve.

The second set of models builds upon the first, assessing the relationships between an area's characteristics and its generation of taxicab trips that act as substitutes for mass transit. Using the same time periods again, this Tobit regression uses a different dependent variable, the share of total trips that are transit substitutes, and models this variable on the same types of independent variables used in the first set of models above. The relationships that these models reveal indicate which areas in Boston exhibit higher concentrations of transit substitution and which types of transit access make substitution more likely.

MODEL 1: RESULTS AND INTERPRETATION

Table V-3 summarizes the results of the best Poisson trip count model specifications for each of the four time periods chosen (with significant variables in bold and insignificant variables shaded).

The first set of models specified reveals significant relationships between taxicab trip counts and several explanatory variables. Furthermore, the variations in these relationships by time of day illustrate how the taxicab's role fluctuates at those different times. These are Poisson regressions, so each regression models the logarithm of block groups' expected trip counts as a function of the independent variables. Thus, a one-unit change in an independent variable's value means that the *logarithm* of that block group's trip count is expected to change by the value of the independent variable's coefficient, all else being equal. The individual components of the trip count models just specified are discussed in greater detail here:

- **Constant coefficients:** Predictably, the constant coefficients for all four time-of-day models vary along with overall levels of average daily taxicab activity (although the overnight constant coefficient is not significant): The evening coefficient is highest (2.64) while the morning peak coefficient is the lowest significant constant (1.78).
- **Block group land area and open space:** Both of these variables also exhibit the expected relationships with taxicab trip generation. A block group's total land area directly affects its trip generation because larger block groups will encompass more taxicab activity on their streets. Similarly, open space is unlikely to generate taxicab trips to the degree that other urban land uses do, especially because sections of urban parkland are often inaccessible by road.

	6:00 - 9:00 am			4:00 - 7:00 pm			8:00 - 11:00 pm			2:00 - 5:00 am		
	Coef	Std Err	Z	Coef	Std Err	Z	Coef	Std Err	Z	Coef	Std Err	Z
Constant	1.78	0.23	7.64	2.32	0.20	11.49	2.64	0.20	13.07	0.28	0.45	0.63
Land area (km ²)	1.05	0.13	8.30	1.65	0.10	16.52	1.26	0.11	11.64	1.01	0.29	3.53
Open space (km ²)	(0.51)	0.17	(3.05)	(1.16)	0.13	(8.68)	(0.46)	0.14	(3.27)	(0.63)	0.38	(1.68)
Airport (dummy)	(1.71)	0.46	(3.73)	(5.04)	0.34	(14.62)	(3.68)	0.40	(9.30)	(3.23)	1.12	(2.89)
Commercial land use (%)	1.60	0.10	16.01	1.94	0.09	22.55	1.60	0.08	20.03	1.88	0.18	10.28
Non-res. building vol. (1,000,000 m ³)	0.04	0.01	5.11	0.04	0.01	6.86	0.03	0.01	5.10	0.04	0.01	2.63
Zero-car households (%)	(0.34)	0.19	(1.80)	(0.26)	0.17	(1.51)	(0.03)	0.17	(0.19)	0.06	0.36	0.17
Population (1,000)	0.44	0.04	11.91	0.30	0.03	8.69	0.15	0.04	4.27	0.35	0.07	5.27
Med. household income (\$10,000)	0.06	0.01	4.40	0.03	0.01	2.51	(0.00)	0.01	(0.30)	(0.03)	0.03	(1.25)
Bus routes	0.04	0.00	7.11	0.05	0.00	12.15	0.05	0.00	11.56	0.04	0.01	4.83
Major bus routes	(0.16)	0.02	(8.28)	(0.05)	0.02	(3.57)	(0.09)	0.02	(5.37)	(0.06)	0.03	(2.05)
Distance from Blue Line (log)	0.12	0.01	10.81	0.03	0.01	3.28	(0.03)	0.01	(3.55)	0.10	0.02	4.50
Distance from Green Line (log)	(0.14)	0.01	(16.31)	(0.22)	0.01	(25.85)	(0.27)	0.01	(31.98)	(0.19)	0.02	(11.68)
Distance from Red Line (log)	0.02	0.01	2.07	0.08	0.01	7.96	0.13	0.01	11.81	(0.00)	0.02	(0.16)
Distance from Orange Line (log)	(0.01)	0.01	(0.78)	0.04	0.01	4.54	0.06	0.01	7.21	0.02	0.02	1.24
Silver Line (dummy)	0.05	0.05	1.08	0.13	0.04	3.10	0.19	0.04	4.48	0.15	0.10	1.50
Distance from center (km)	(0.36)	0.02	(21.01)	(0.42)	0.02	(22.50)	(0.42)	0.02	(21.72)	(0.22)	0.03	(7.36)
Intersections (100 per km ²)	(0.29)	0.03	(9.66)	(0.34)	0.03	(12.34)	(0.22)	0.02	(9.85)	(0.16)	0.06	(2.86)
Class 1 road (dummy)	0.21	0.06	3.72	(0.24)	0.05	(4.46)	0.09	0.05	1.72	(0.01)	0.11	(0.05)
Class 2-4 road (km)	0.02	0.02	1.22	0.10	0.02	6.12	0.10	0.02	6.12	0.02	0.04	0.45
Pseudo R ²	0.775			0.887			0.850			0.634		
LR	10599			27492			23295			2160		
Total observations	544			544			544			544		

Table V-3: Results of Poisson taxicab trip generation models

Certain block groups with large expanses of open space will therefore not generate the same concentrations of taxicab pickups that commercial or residential urban fabric would. In all four models, land area has a significant positive relationship with taxicab pickups and open space has a significant negative relationship with pickups. Both relationships are strongest during the afternoon peak.

- **Logan Airport dummy variable:** Because the airport is an outlier in Boston's taxicab market (and in many other cities), and because roughly 20 percent of Boston taxicab trips begin or end at Logan, a dummy variable is included in the models to correct for any distortion that it may cause as a trip generator. This airport dummy variable has a significant relationship to taxicab trip generation during all four time periods and its coefficient is always negative, with the strongest inverse relationship to taxicab pickups occurring in the afternoon peak. Despite the airport's high taxicab trip generation, other characteristics of its block group (such as land area) would potentially cause these models to predict even higher trip counts for it, which is why the dummy variable's coefficient takes negative values throughout the day.
- **Population and socioeconomic characteristics:** The positive relationship between population and trip generation is intuitive: People are the source of demand for trips, and more residents in a block group should result in more trips, all else being equal. Population only tells part of this story, however, as non-residential areas generate some of the highest trip counts in Boston. If people are traveling from their homes to other activities by taxicab, population (which reflects individuals' places of residence) captures a portion of that effect. The role of non-residential sources of trip generation, on the other hand, is discussed below. In addition to population, median household income has a positive

relationship with taxicab trip generation during the morning and afternoon peaks, an insignificant relationship to evening activity, and a negative relationship with overnight taxicab pickups. Most likely, many who can afford to commute to work by taxicab earn high incomes and place greater values on their time. During the overnight period, lower-income people may represent a higher share of all taxicab passengers, and this relationship supports the taxicab's role as a complement to transit during the hours when transit does not operate. Of course, lower-income travelers may also account for a larger share of all travel demand during the overnight period, which would also help to explain the negative correlation between income and taxicab trips at that time. Finally, the percentage of households that own no cars exhibit a significant inverse relationship with taxicab trip generation during only the morning and afternoon peak periods. This negative relationship is not necessarily surprising because urban car owners may have an aversion to transit use and take taxicabs when not driving themselves, especially when parking will be scarce at their destinations. As an additional note, the percentage of zero-car households in Boston exhibits an inverse correlation of -0.61 with median household income, so much of the relationship between car ownership and taxicab trip generation is reflected by the income coefficients (see Appendix).

- **Land use and built environment:** Two independent variables, the share of a block group's land area dedicated to commercial use and the total non-residential building volume within each block group, both have significant positive relationships with taxicab activity throughout the day and are not strongly correlated. As mentioned above, population acts as a proxy for residential trip generation, while these two variables together approximate non-residential trip generation. Non-residential building volumes in downtown Boston dramatically

exceed those found in peripheral parts of the city, reflecting the great intensity of non-residential uses (and trip generation) that one finds there. Commercial land use share captures additional trip generation that does not correspond to building volume, especially outside of downtown Boston.

- **Urban form and relative location variables:** Several indicators of urban form have significant relationships with taxicab trip generation in Boston. First, a block group's straight-line distance from Boston's center¹⁷ is negatively related to trip generation, all else being equal. In other words, peripheral block groups generate fewer trips than central block groups, even after controlling for transit access and the above indicators. This outcome makes sense, as Boston's taxicab supply is expected to be more centrally concentrated (even beyond what land use indicators might predict, as discussed in earlier chapters). Additionally, driving one's own car and finding parking is easier at greater distances from Boston's center, which would also lead to lower taxicab activity on the periphery, where the car would be the taxicab's chief competitor. Finally, in less central locations, people's lifestyles are more oriented toward travel patterns that favor the car and not the taxicab. These tendencies should all contribute to more realized demand in more centrally-located places, all else being equal. Additional urban form indicators that are significant include intersections per square kilometer, whether a Class 1 roadway (limited access highway) intersects the block group, and the

¹⁷ I arbitrarily define Boston's central point as City Hall and measure all other block groups' centrality distances from that reference point.

total length of Class 2, 3, and 4 roadways within a block group. More intersections (and presumably smaller blocks) result in fewer taxicab pickups, suggesting that such urban environments are more accommodating to walking and transit use and will thus generate fewer taxicab trips. Class 1 roadways have the opposite effect during the morning and evening, and again this is perhaps because of their negative impact on the urban environment and walkability, which would encourage taxicab usage. Class 1 roadways have a negative relationship with taxicab trip generation during the afternoon peak, however. The variance of this relationship is potentially explained by different trip characteristics at different times: If passengers are in a greater hurry in the morning peak or evening, they may gravitate toward Class 1 roads if they expect to hail a taxicab more easily in those places. The presence of other major roads (Classes 2, 3, and 4) has a positive correlation with trip generation throughout the day, but this is most likely a result of better taxicab supply along these types of roads.

- **Transit access variables (rail):** Having controlled for the aforementioned variables in these models, we can observe specific relationships between different types of transit access (as defined in Chapter Four) and taxicab trip generation. In general, evidence of a transit substitution effect is observed for several MBTA rail lines: A block group's proximity to the Red Line, Orange Line, and Blue Line results in fewer taxicab pickups, all else being equal,¹⁸ although

¹⁸ Controlling for block groups' distance from Boston's center is important to the interpretation of the transit coefficients, since centrally-located block groups also have better transit access; the distance variable allows us to identify transit's impact after accounting for centrality.

this effect reverses itself on the Blue Line in the evening period (and is insignificant for the Red Line overnight¹⁹ and for the Orange Line in the morning). Distance from the Green Line, on the other hand, exhibits a *negative* correlation with taxicab trip generation at all times of day. That is, a block group's proximity to a Green Line station actually increases its taxicab trip generation. This is also true of the Silver Line throughout the day, although a dummy variable indicates Silver Line proximity. During the evening time period, distance from the Red Line and Orange Line exhibit their strongest positive relationships to trip generation and Green Line access has its strongest negative relationship to taxicab pickups in the evening as well. These results seem to indicate that the taxicab is, in fact, something of a complement to rail transit, but few broad generalizations are possible from the relationships observed here. The specific model coefficients for each line offer helpful clues about the nature of taxicabs and transit in Boston, however. For a few MBTA lines—especially the Red Line, but also the Orange Line and Blue Line at certain times—taxicab trip generation decreases nearer their stations. This appears consistent with a complementary relationship between taxicabs and transit, in which passengers find taxicab travel more necessary (and its relative utility higher) when transit is less accessible due to

¹⁹ The transit distance variables are still included in the overnight trip generation model despite their lack of service between 2:00 and 5:00 a.m., and three of these variables are significant during that period. I include these in the overnight model due to the possibility that transit service itself is not the aspect of transit distance that is most relevant to taxicab activity. For example, transit station locations represent some of the densest concentrations of travel demand in urban areas like Boston, even after controlling for many other variables.

distance. The Red Line offers high service levels along a dense corridor of travel demand, so individuals beginning trips near a Red Line station will find it to be a more reasonable alternative to the taxicab for many trips. Importantly, this relationship weakens to insignificance during the overnight period when the Red Line does not run.²⁰ In the Green Line's case, the opposite relationship between the modes is observed: The nearer a Green Line station, all else being equal, the more taxicab activity occurs. Like the Red Line, the Green Line follows a dense corridor of travel demand, connecting Boston's CBD, the Back Bay, and Boston University. The sharp distinction between the Green Line's relationship to taxicab pickups and the Red Line's may be explained by several differences between the two corridors: The Green Line is a light rail line that travels quite slowly in places and must stop for traffic due to its at-grade operation. Furthermore, choosing a taxicab over transit may be easier for passengers waiting at the Green Line's busy street-level stations. Finally, demand itself may be different on each line, with more tourists and others who rely heavily on taxicabs concentrated near the Green Line and not explained by other variables in these models. Like the Green Line, the Silver Line and the evening-period Blue Line have more taxicab activity nearer their stations. The Silver Line's coefficients can potentially be explained by its lower service levels and slower speeds in comparison with heavy rail transit, as I suggested for the Green Line. The Blue Line's service does not

²⁰ A substantial portion of the Red Line operates outside of Boston, so many taxicab trips that begin near its stations are not observed in this analysis, potentially weakening the modeled relationships. The same is true to lesser degrees for the other MBTA rail lines.

explain its negative evening coefficient, but the line may simply be less useful to passengers during the evening period than during the peaks (especially if used for longer-distance work trips more than for discretionary trips). As a final note, some taxicab trips that begin near rail stations do not serve destinations that rail also serves, and the second set of models will provide more insight into where transit substitution is occurring. Nevertheless, these transit access coefficients provide evidence that taxicab service levels, to the extent that they are manifested as realized demand, sometimes increase along with distance from transit stations and sometimes decrease. These relationships are not always even consistent for a single rail line throughout the day. This suggests that the taxicab may play a gap-filling role and a duplicative role with respect to the MBTA rail network under different circumstances.

- **Transit access variables (bus):** Two indicators of bus access measure total MBTA bus routes and major bus routes intersecting a block group, respectively. Interestingly, total bus routes are positively related to taxicab trip generation throughout the day while major bus routes are inversely related to trip generation. One possible explanation for this divergence is that the MBTA's highest-frequency bus routes provide sufficient service levels to attract passengers that might otherwise use taxicabs, while its overall bus service is not frequent enough to accomplish this and actually loses passengers to the taxicab. The coefficients for the variable representing major bus routes have their most extreme value during the morning peak, when this bus service is more frequent. When transit service is poor, under this hypothesis, the taxicab's role as a substitute to transit is encouraged.

The variation in taxicab pickups that is not explained by these models manifests itself as their residuals, which are mapped in Figure V-13 and Figure V-14. Residuals for both sets of models are calculated by subtracting the models' predicted values from the actual observed values for each census block group, and these values are "studentized" by dividing each residual value by its standard deviation. The residuals for the first set of models are important in their ability to hint at which parts of Boston the taxicab underserves. Negative residuals represent instances when the model overestimates a block group's actual trip generation, and if these block groups have characteristics that generally reflect high taxicab demand then we have reason to believe that unmet demand (as opposed to realized demand) exists there. During the four time periods modeled, Roxbury and Jamaica Plain seem to have "overestimated" trip generation, as do Charlestown, East Boston, South Boston, and Allston. Parts of these areas also have poor access to rail transit, meaning the taxicab is failing to fill specific gaps in Boston's public transportation network. Further investigation would be worthwhile to confirm the existence of unmet demand in these locations.

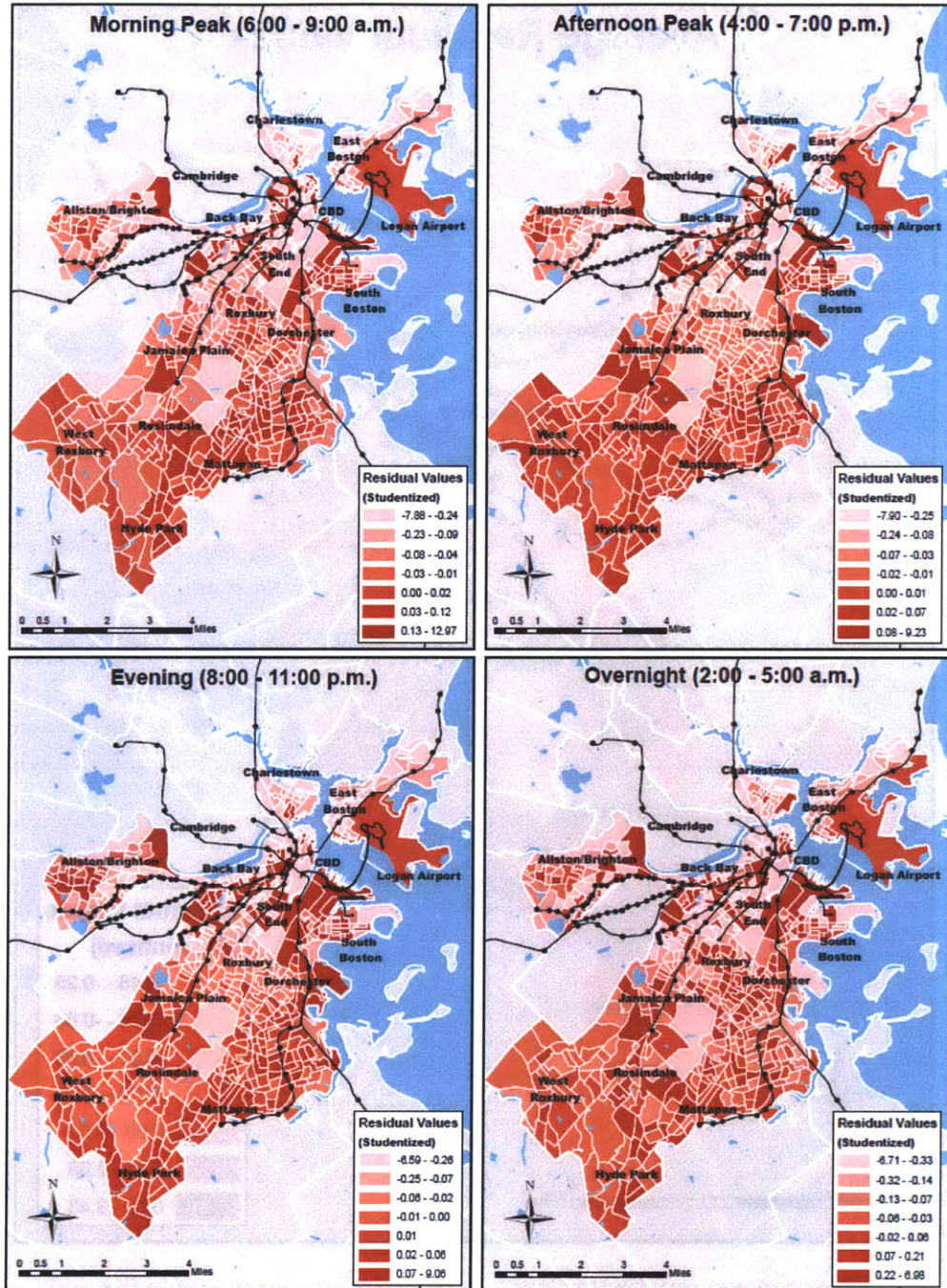


Figure V-13: Residuals of Poisson trip generation models

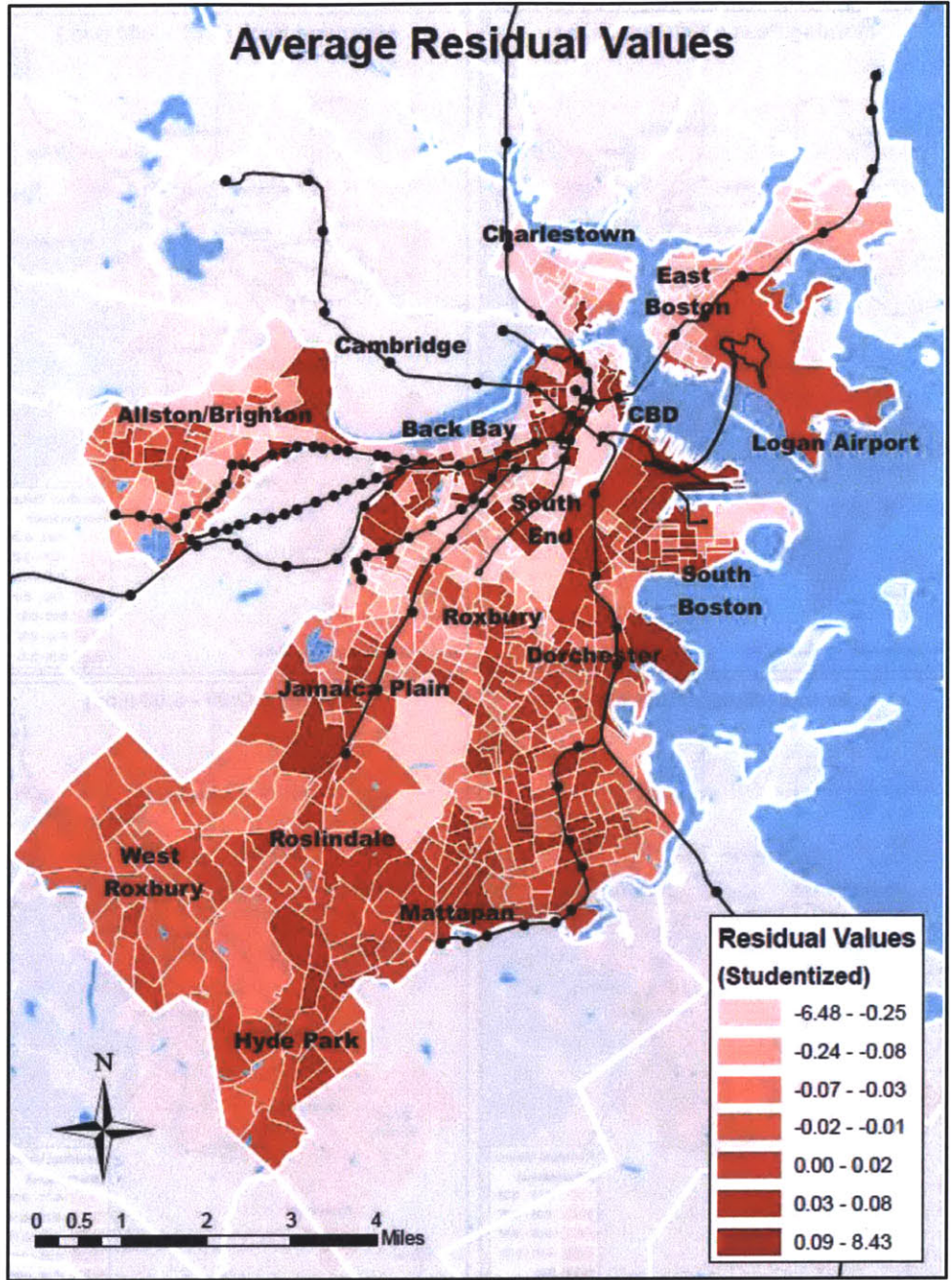


Figure V-14: Average residual values of Poisson trip generation models

MODEL 2: RESULTS AND INTERPRETATION

Table V-4 summarizes the results of the best Tobit transit substitute share model specifications for each of the three time periods chosen (with significant variables in bold and insignificant variables shaded).

This second set of models offers more limited insights than the first set does. These Tobit models express relationships between a variety of block group characteristics and the share of taxicab trips originating in a given block group that are transit substitutes; however, fewer significant relationships emerge from the models specified, and different times of day yield different explanatory factors. I do not specify a transit substitution model for the overnight time period because negligible transit service is available then, making substitution by taxicab (as I have defined it) impossible. The individual components of these models are summarized here:

- **Constant coefficients:** None of the constant coefficients for the three time period models I specify are significant. Thus, no clear distinctions among the levels of transit substitution across the three time periods are observed when all else is equal.
- **Land use variables:** Open space (as a share of total land area) has a positive relationship with transit substitution share during the morning peak and evening periods. Open space may encourage transit substitution through its association with lower transit service levels or longer average walking distances to reach transit stations. The share of a block group's land area dedicated to commercial use also has a consistent, positive correlation with transit substitution. The most plausible reason for this is that commercial areas attract individuals with higher willingness to pay and thus generate more discretionary trips from travelers

	6:00 - 9:00 am			4:00 - 7:00 pm			8:00 - 11:00 pm		
	Coef	Std Err	t	Coef	Std Err	t	Coef	Std Err	t
Constant	(0.04)	0.24	(0.17)	0.19	0.27	0.72	0.20	0.30	0.67
Commercial land use (%)	0.29	0.13	2.25	0.35	0.15	2.34	0.31	0.17	1.82
Open space (% of land area)	0.38	0.13	2.96	0.14	0.15	0.91	0.32	0.17	1.93
Zero-car households (%)	0.08	0.19	0.42	(0.09)	0.22	(0.44)	0.04	0.24	0.19
Pop. density (1,000 per km ²)	0.00	0.00	0.67	0.01	0.00	1.76	0.00	0.00	0.97
Med. household income (\$10,000)	0.00	0.02	0.24	0.01	0.02	0.36	(0.01)	0.02	(0.29)
Bus routes	0.00	0.00	0.96	0.01	0.01	2.30	0.01	0.01	1.88
Major bus routes	0.02	0.01	1.70	0.01	0.02	0.89	0.02	0.02	0.90
Distance from Blue Line (log)	0.04	0.01	2.86	0.03	0.01	1.73	0.01	0.02	0.84
Distance from Green Line (log)	(0.04)	0.01	(5.01)	(0.06)	0.01	(7.11)	(0.07)	0.01	(6.93)
Distance from Red Line (log)	(0.03)	0.01	(3.30)	(0.02)	0.01	(2.07)	(0.02)	0.01	(1.45)
Distance from Orange Line (log)	0.01	0.01	1.57	0.01	0.01	0.63	0.01	0.01	0.86
Silver Line (dummy)	0.15	0.05	2.84	0.08	0.06	1.32	0.09	0.07	1.25
Distance from center (km)	(0.05)	0.01	(4.81)	(0.05)	0.01	(3.75)	(0.04)	0.01	(2.77)
Intersections (100 per km ²)	0.06	0.03	2.20	0.00	0.03	0.05	0.02	0.04	0.50
Pseudo R ²	0.353			0.357			0.296		
LR	251			262			225		
Total observations	544			544			544		
Left-censored observations	320			344			342		

Table V-4: Results of Tobit transit substitution models

whose preference for taxicab travel tends to override their consideration of mass transit use. Tourists, for example, are more likely to spend their time in Boston's commercial areas than in its residential areas, and shoppers often return from their trips with the merchandise they have purchased, which makes taxicab travel more preferable relative to transit.

- **Population and socioeconomic characteristics:** In general, the three population and socioeconomic variables included in these models have insignificant relationships with transit substitution. The one exception to this is population density, which has a positive relationship with transit substitution share during the afternoon peak. Otherwise, population density, percentage of zero-car households, and median household income exhibit no significant correlations with transit substitution by taxicabs, suggesting that demographic characteristics have little to do with transit substitution after controlling for other factors.
- **Urban form and relative location variables:** Certain indicators of urban form and location within Boston have significant relationships to block groups' transit substitution shares: Distance from Boston's center has a negative relationship with transit substitution, meaning block groups farther from Boston's center generate fewer trips that are transit substitutes. Because transit access is also a part of this model, the effect of centrality goes beyond the fact that transit access is better in Boston's center. Interestingly, taxicab service that these peripheral areas do receive appears to fulfill a more complementary role, in general. In addition to centrality, intersection density has a significant positive correlation with transit substitution during only the morning peak, possibly reflecting other unobserved variables. There is no clear reason why intersection density would

only relate to transit substitution during the morning, but smaller blocks and more fine-grained urban fabric may encourage people to travel by a variety of public transportation modes, including the taxicab, instead of driving.

- **Transit access variables:** The most important products of these Tobit models are the revealed relationships between transit access and transit substitution.

Although transit access is a prerequisite for all transit substitution, the variable relationships observed for separate lines and modes are of great interest here. At all times of day, a block group's proximity to the Green Line, as well as the Red Line and Silver Line (to lesser degrees), make transit substitution more likely. Conversely, proximity to the Orange Line and Blue Line make transit substitution less likely, but only at certain times of day (the morning for both lines, and the afternoon peak for the Blue Line). Finally, access to bus routes within a block group has a slight positive effect on transit substitution. Major bus routes have a significant relationship to substitution in the morning, and total bus routes are significant during the afternoon and evening. The observation that the Green, Red, and Silver lines are most likely to be duplicated by taxicabs could mean several things. For one, the concentrations of demand along those corridors may comprise the passengers most likely to choose taxicabs over transit. A second explanation is that the higher concentrations of taxicabs along those lines make the taxicab more competitive with transit. Alternatively, the particularities of a corridor's travel demand could explain these variations: If people primarily use the Blue Line for commuting, these trips will be less likely to occur by taxicab, but discretionary travel is more likely to occur by taxicab. The Green and Red lines both demonstrate a correlation with trip counts in the first set of models, which supports the conclusion that taxicab service is simply better near those lines and more competitive with transit service from a relative utility standpoint.

These Tobit models leave a great deal of variation in taxicab substitution share unexplained, and Figure V-15 and Figure V-16 map the distributions of the models' residuals. In the second set of models, the residuals identify places where substitution occurs more or less frequently than expected. In other words, a negative residual indicates a place where transit is more popular or more frequently used than the model predicts it would be (if we interpret lower transit substitution to mean higher transit use, which is not necessarily the case). Not surprisingly, block groups along transit lines—especially the Orange Line and Green Line near downtown Boston, Jamaica Plain, and Allston—had negative residuals. These areas may represent situations where the taxicab plays its ideal role in Boston, substituting for transit less than we would expect and acting as a complement to transit more frequently. Conversely, areas near transit with very high residuals may represent excessive substitution by taxicabs—an outcome that earlier sections of this thesis deem undesirable.

The final chapter, which follows, will further interpret these results and relate them back to the research questions that this thesis has explored. A discussion of the models just specified and the meanings of their residuals will inform a summary of the taxicab's actual and ideal roles in Boston's transportation system.

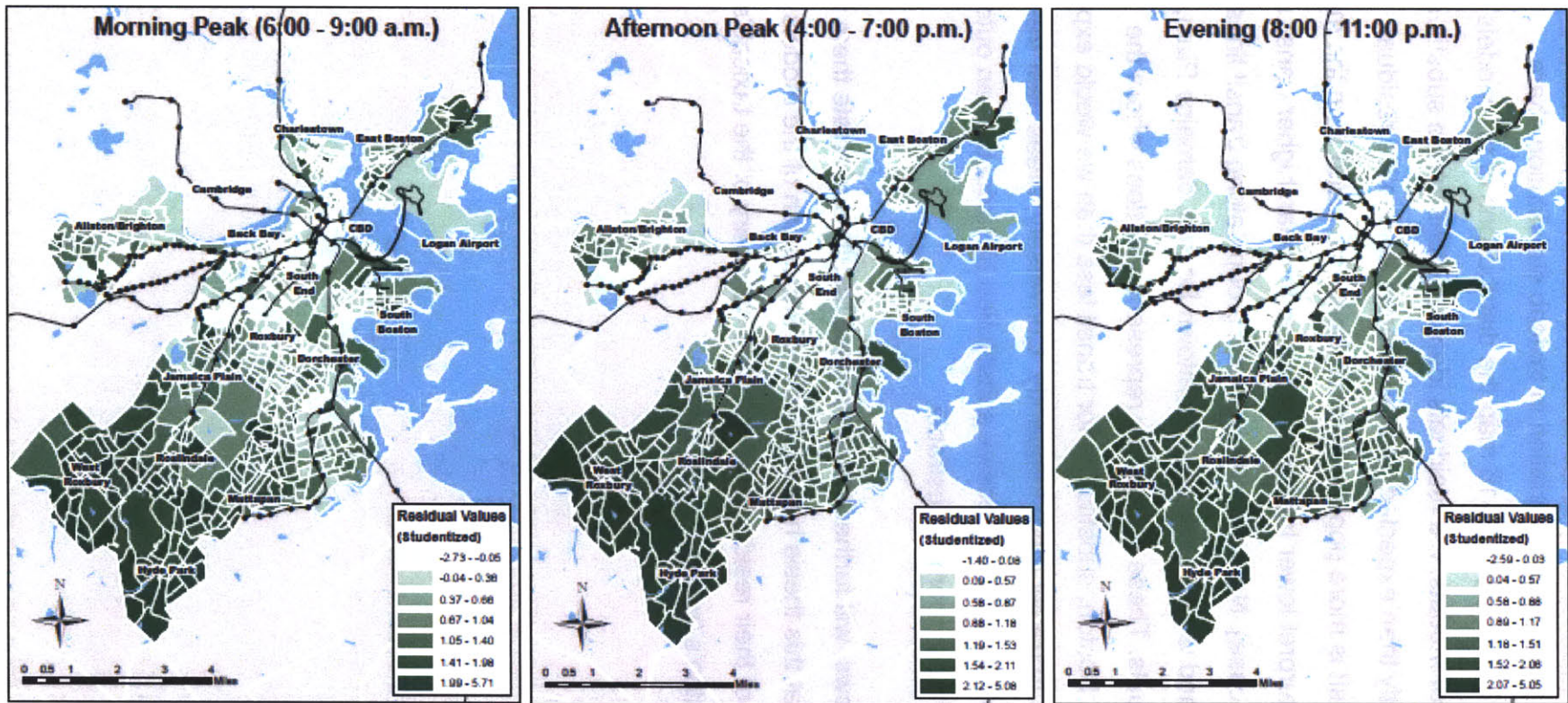


Figure V-15: Residuals of Tobit transit substitution models

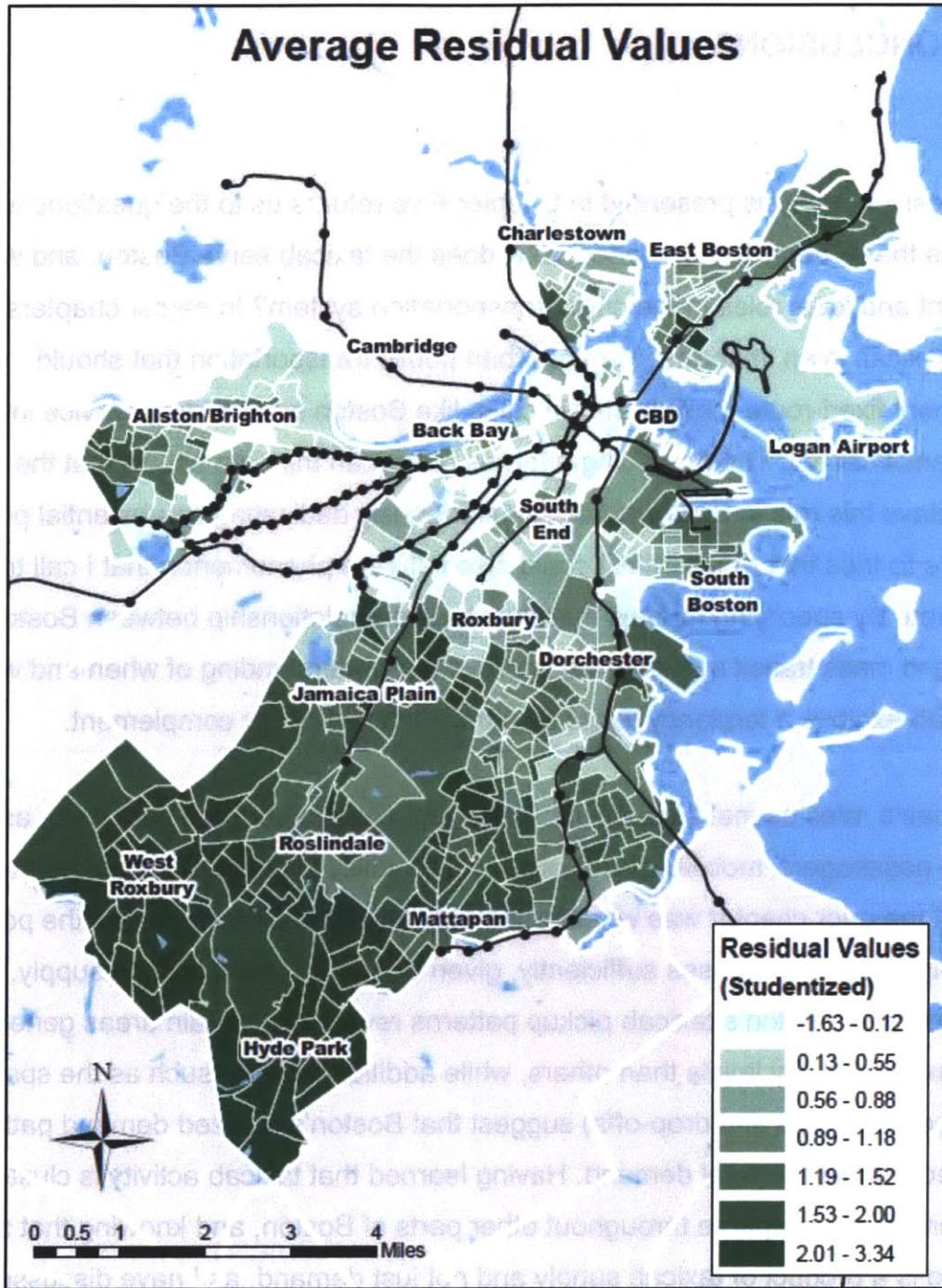


Figure V-16: Average residual values of Tobit transit substitution models

VI. CONCLUSIONS

The regression analysis presented in Chapter Five returns us to the questions with which this thesis began: How, specifically, does the taxicab serve Boston, and what are its present and ideal roles in the city's transportation system? In earlier chapters, I argue that the taxicab is an important form of urban public transportation that should complement fixed-route mass transit in cities like Boston by providing service in places where transit cannot. The preceding analysis of taxicab trip data shows that the taxicab system plays this role in Boston while simultaneously dedicating a substantial portion of its service to trips that mass transit could also fulfill—a phenomenon that I call transit substitution. By specifying models that illuminate the relationship between Boston's taxicab and mass transit systems, we improve our understanding of when and where the taxicab exhibits a tendency to act as a transit substitute or complement.

The taxicab's roles as mass transit substitute and complement are both valid, as both enhance passengers' mobility and maximize their utility in different instances. A key inquiry of the prior chapter was whether the taxicab accomplishes (or has the potential to accomplish) both purposes sufficiently, given Boston's limited taxicab supply. Observations of Boston's taxicab pickup patterns reveal that certain areas generate higher taxicab activity levels than others, while additional clues (such as the spatial imbalance of pickups and drop-offs) suggest that Boston's realized demand patterns do not perfectly match its total demand. Having learned that taxicab activity is clustered in certain areas and is sparse throughout other parts of Boston, and knowing that such clustering is a product of taxicab supply and not just demand, as I have discussed in earlier chapters, the taxicab almost certainly underserves certain parts of Boston.

Transit access also varies throughout the city, and gaps in the system—places with below-average transit access—lack a “public” form of mobility that the taxicab could potentially provide. Identifying the existence of unmet travel demand within these gaps would confirm this condition, and the regression analysis conducted in Chapter Five was an initial step toward doing so. Future analyses of taxicab service in Boston should investigate the areas that these models’ residuals identify as potentially underserved by both taxicabs and transit.

Regression modeling thus achieves two important purposes for the research objectives of this thesis by identifying possibly underserved areas in Boston and specific opportunities for improving the distribution of taxicab service in the city. The value of analyzing Boston’s taxicab activity using regression lies in the relationships that analysis reveals. The previous chapter’s models yielded results that fall into three major groups: Fixed and relatively unchangeable qualities of the urban environment; transit access; and unexplained variation (the models’ residuals). Each of those three groups reflects different relationships to taxicab activity, with different implications for identifying shortcomings in taxicab service levels and remedying those shortcomings.

The first set of models specified in Chapter Five focuses on trip generation, which is a proxy if not a precise indicator of taxicab service levels. Grouping these models’ explanatory variables according to whether they impact taxicab supply or demand allows us to infer where unmet demand exists. High building volumes, a high share of commercial land use, and high incomes lead to higher trip generation, most likely, by creating demand for taxicab travel. Centrality, on the other hand, primarily influences the supply side of realized demand, as the literature has pointed out tendencies for cruising taxicabs to cluster in downtown areas (Frankena and Pautler 1984; Yamamoto

et al. 2008). If a census block group in Boston has few taxicab pickups despite characteristics that predict high demand for the mode, as well as supply characteristics that predict low realized demand, the evidence presented thus far gives reason to believe that unmet demand exists in that location. These models' residuals show which parts of Boston diverge from their predictions, and locations with negative residuals as well as qualities expected to negatively impact taxicab supply are the most likely to be underserved. These conclusions should nonetheless be viewed as tentative, however: A number of potentially relevant variables are omitted from these models, and future research will ideally pick up where mine has left off by improving their specifications.

POTENTIAL TAXICAB INTERVENTIONS

The model results just presented allow us to infer specific locations where unmet taxicab demand is most likely to exist and the circumstances in which taxicabs are most likely to act as transit substitutes. This thesis has argued that the taxicab should complement transit by filling gaps in the transit system, and having analyzed the two modes' relationship, I summarize potential interventions to the Boston taxicab industry that might produce a more favorable distribution of taxicab service. I also acknowledge any obstacles that could inhibit these interventions.

The most viable opportunities to improve Boston's taxicab system are smaller-scale interventions rather than comprehensive adjustments to the industry. The two most important regulatory mechanisms for taxicabs in Boston and many other cities, described in Chapter Three, are medallions and fixed fare rates, but both of these are virtually impenetrable as objects of reform. An extensive literature has examined the advantages and disadvantages of limiting a city's taxicab supply by fixing the number of available medallions and many compelling arguments exist on both sides of the matter.

Due to medallions' enormous value, however, eliminating the medallion system altogether would require the City to buy out the 1,825 medallion holders for hundreds of thousands of dollars each. The City did manage to increase the total number of medallions during the 1990s, but even that marginal increase involved a prolonged legal battle. Taxicab fare rates, if lowered, would meet with similar opposition due to the negative effect that such a change would have on individual drivers' revenues. For the problems I address in this thesis, however, aggregate changes to medallion totals or fares would be unlikely to improve service levels in specific underserved areas or encourage the taxicab to complement mass transit. More nuanced approaches are better suited to helping achieve these objectives.

In order for the taxicab to function as public transportation in Boston and to complement mass transit more effectively, its role as paratransit (as Cervero has defined the term) should be acknowledged and actively encouraged. In U.S. cities, the dominance of the private automobile as a transportation mode means that other modes compete with the car more than they compete with each other. Carsharing services like Zipcar, bike-sharing programs, university campus shuttles (and other privately-operated shuttles), and other forms of paratransit, along with the taxicab, all play different roles in allowing people to live in cities like Boston without relying upon a car that they own. Many of these transportation services are widespread in Boston, and others, such as bike sharing, are being developed. Boston's large taxicab supply, and those taxicabs' ability to fill niches that other paratransit modes and mass transit do not, represent an opportunity to further improve urban mobility by diversifying the types of service that taxicabs offer. Cervero (1997) and Gilbert and Samuels (1982) have recognized that shared-ride taxicab service can benefit both passengers and drivers where allowed by enabling the taxicab to function more like transit. The data I present in this thesis

demonstrates the opportunity to pinpoint spatial and temporal concentrations of taxicab origin-destination pairs, which the City could use to designate taxicab ridesharing zones. Likewise, Boston's ability to monitor real-time taxicab movements and the increasing prevalence of smart phone technology could enable more sophisticated approaches to such ridesharing. Gilbert and Samuels point out that, in general, the taxicab industry should offer more types of service than the exclusive-ride service which predominates in Boston and elsewhere.

The taxicab might also dovetail with mass transit in a more direct sense: Some service that one of the two modes currently provides may be provided more efficiently by the other. If concentrations of realized or unmet taxicab demand are found that indicate a sufficiently high density of demand between a given origin and destination, a bus route may be able to serve this demand more efficiently than taxicabs. Of course, additional knowledge of passengers and trip types would be necessary to confirm that these passengers would actually switch from taxicab to transit. Similarly, bus routes with very low ridership may not be the most cost-effective means of fulfilling the few trips that those routes currently serve. Contractual arrangements between the MBTA and taxicab operators, or informal arrangements like the aforementioned Berkeley example that Cervero (1997) describes, could allow taxicabs to replace poorly-performing bus routes. Gilbert and Samuels (1982) have also advanced the argument that federal transit funding should extend to the taxicab industry as well, but this development would have to occur at the national rather than local level.

Finally, in light of the spatial imbalance of taxicab supply that my research has described, the City should consider interventions that improve taxicab service to areas that are, in fact, underserved. Taxicab stands offer one simple and inexpensive way to

accomplish this. The economics of taxicab supply, discussed in previous sections, favor density of demand, and areas with unmet demand may receive lower taxicab supply if that demand is spread more thinly than in Boston's CBD. Taxicab stands offer the advantage of concentrating this dispersed demand and allowing passengers and taxicab drivers to find each other more efficiently. Of course, creating a taxicab stand does not guarantee that taxicabs will serve it, but the potential might exist to create monetary incentives for taxicab service at certain locations.

DATA COLLECTION RECOMMENDATIONS

The research I have presented in this thesis attempts to answer a series of questions about taxicab supply and demand using records of taxicab trips in Boston. This effort, however, has raised more questions than it has actually answered. In addition to addressing specific questions about the taxicab's service distribution and its relationship to transit, I intend for the work I present in this thesis to serve as an introduction to a type of transportation data that is becoming increasingly available in the urban environment—data which have not yet been explored in great depth. Data of this kind have the potential to answer countless questions about travel behavior, supply, and demand that, until recently, would have required prohibitive time and monetary expenditures to study in comparable detail. A substantial portion of my research is dedicated to determining what this particular data set actually tells us, as realized demand provides an incomplete picture of total travel demand. Refinements to the taxicab data collection process might enable these data to answer a broader range of questions with greater certainty in the future. Additionally, research that uses the existing data available from the City of Boston can build substantially upon my own work, the scope of which has necessarily been limited.

A number of opportunities to improve Boston's taxicab data emerge from this thesis, many of which could be relatively easy to implement. A few of the most basic improvements by which the City could enhance understanding of Boston's taxicab system, especially in light of the questions I have addressed, include the following: data about taxicab dispatching activity, more detailed records of taxicabs' routes, and information about taxicabs' non-revenue activity between passenger trips. An explanation of each follows:

- **Dispatching:** At the most basic level, dispatching data could include a record of whether or not each passenger trip originates in response to a dispatch request (as opposed to a street hail). A driver could easily indicate this at the start of any such trip. The time of the dispatch request would also prove useful, although recording this would require the integration of taxicabs' data collection capabilities with dispatch houses' records and matching the two could be difficult. The value of dispatch information lies in the relationship between dispatching and taxicab levels of service: If a large share of an area's realized taxicab trips originate by radio dispatch request, this means that waiting times for these trips are longer and taxicab service levels are lower. Cruising taxicab service, by contrast, represents a higher service level in a given location. Knowing how service is obtained in a location tells as much about the interaction of taxicab supply and demand as knowing the number of trips that originate there.
- **Route data:** In addition to recording taxicab trips in their databases, CMT and Verifone track Boston taxicabs in real time. This detailed knowledge of taxicabs' locations should be recorded and stored at some level of precision. The current trip databases include taxicab medallion numbers and trip distances, which facilitate a basic understanding of a single taxicab's activity throughout the day,

but periodic records of a vehicle's precise location, in addition to the locations of its passenger pickups and drop-offs, would illustrate in much greater detail how taxicabs move throughout the city. For example, each vehicle's location could be recorded at a regular, frequent interval. Traffic planners could use these data to understand traffic patterns and path selection, while taxicab researchers could gain insight into how taxicabs cruise for passengers—a critical element of taxicab supply.

- **Non-revenue taxicab data:** As noted above, knowledge of a taxicab's activity between passenger trips facilitates an understanding of overall taxicab supply. In addition to route and location information, it would be helpful to record drivers' breaks and shift changes, as this would provide a more precise picture of how much time taxicabs spend cruising. This information, if combined with more detailed route information discussed above, could enable estimates of the spatial and temporal distributions of empty and occupied taxicabs. As Douglas (1972) explained, this is an important indicator of taxicab supply. Knowing where taxicabs cruise offers information that realized demand (trip records) does not. Of course, non-revenue data that drivers themselves would have to record manually would be subject to inaccuracy, and drivers may choose not to volunteer this information for a variety of reasons.

At a higher level, two additional actions could potentially improve the utility of Boston's taxicab data: making that data more widely available to researchers or the general public, and collecting similar data for taxicabs in other Boston-area municipalities, such as Cambridge, Brookline, and Somerville. The first of these actions is within the City of Boston's capabilities while the second is not. The value of opening these records to more individuals is possibly great, although risks accompany the potential benefits:

Open data have proven to facilitate rapid innovation in a variety of fields, and making taxicab data available to more researchers would simply accelerate the collective understanding of the taxicab industry in Boston and in general. Opening taxicab data to the general public could yield private sector innovation that enhances the taxicab's utility for passengers as well as operators, as research I summarized in Chapter Two has suggested. The MBTA's success in generating a number of low-cost (or costless) privately-developed transit information applications by opening up its data for public use suggests that similar results might be possible for the taxicab industry. Despite these advantages, however, opening taxicab data poses potential risks: In such a competitive industry, widely disseminated knowledge of taxicab activity could potentially distort the market in unforeseen ways, to the disadvantage of certain operators or passengers. In particular, open data could enable operators to identify which parts of Boston are most profitable to serve at different times of day, potentially *widening* the service gap between areas with good and poor taxicab service—the opposite of what this thesis has recommended. The City should certainly weigh the positive and negative consequences that might result from opening its taxicab data to a wider audience and it should consult industry stakeholders, especially taxicab operators, about the wisdom of doing so.

Improving taxicab data collection in the municipalities that surround Boston, although beyond Boston's ability to implement, would also enhance our understanding of taxicab activity between municipalities in Boston's metropolitan area. As pointed out in previous sections, taxicab travel between Boston and its surroundings is incompletely represented by Boston taxicab data alone, as other cities' taxicabs fulfill much of that demand. Each city would have to implement its own data collection system, probably by requiring all taxicabs to install credit card processing (as Boston did). The cost of requiring this would potentially discourage some cities from doing so, but even a few

larger taxicab systems (such as Cambridge's) could fill valuable knowledge gaps by collecting taxicab trip data as Boston does.

OPPORTUNITIES FOR FUTURE RESEARCH

The rich taxicab data set I explore throughout this thesis and the questions I ask about taxicab demand raise countless questions about the taxicab industry that could easily form the foundations of many more theses. The lack of research using taxicab trip data of this kind has required me to direct much of my own effort toward understanding what trip data can even tell us with any certainty. Regarding my questions about the distribution of taxicab activity, improvements to the regression models I have specified are certainly possible, and any significant variables that impact taxicab activity in important ways should be sought and added to these models. Additionally, future research should explore the potentially underserved areas that these models' residuals have identified by examining those specific areas in great detail and assessing their specific transportation problems in depth. Finally, travel surveys would provide an incredibly valuable source of data about taxicab users that could be paired with these taxicab trip data to answer various questions about which I could only guess in my work, including questions about the actual interactions between taxicab supply and travel demand. A mode choice model of the taxicab and mass transit could potentially be specified using comprehensive travel survey data of this kind. Beyond my own research questions, of course, many more arise from an examination of Boston's taxicabs, and I will not try to enumerate all of those questions here. One fruitful avenue of inquiry, though, would be the study of individual taxicabs' behavior using medallion and driver identification numbers. The economics of taxicab supply and the determinants of certain drivers' operational patterns could provide incredible insight into many facets of urban transportation. By learning where individual taxicab drivers go, we can understand how

they respond to experience and whether they adjust their driving behavior according to the profitability of various operating modes. Understanding these behavioral elements of transportation supply and their broader impacts on urban transportation are just one of the inquiries that nuanced data sets of the kind I have explored might enable us to pursue much further.

VII. BIBLIOGRAPHY

- Alexander, C., S. Ishikawa, and M. Silverstein (1977). *A Pattern Language: Towns, Buildings, Construction*. New York: Oxford University Press.
- Arnott, R. (1996). "Taxi Travel Should Be Subsidized." *Journal of Urban Economics* 40: 316-333.
- Beesley, M. E. and S. Glaister (1983). "Information for Regulating: The Case of Taxis." *Economic Journal* 93: 594-615.
- Beimborn, E. A., M. J. Greenwald, and X. Jin (2003). "Impacts of Transit Accessibility and Connectivity on Transit Choice and Captivity." *Transportation Research Record* 1835: 1-9.
- Berdik, Chris (2004). "Fare Game." *Boston Magazine*, September 2004.
- Bossard, E. G. (2002). *Envisioning Neighborhoods with Transit-Oriented Development Potential*. US Department of Transportation Research and Special Programs Administration, California Department of Transportation, and Mineta Transportation Institute, MTI Report 01-15. Springfield, VA: Mineta Transportation Institute.
- Boston Police Department (2008). *Rule 403: Hackney Carriage Rules and Flat Rate Handbook*. Boston, MA.
- Cairns, R. D. and C. Liston-Heyes (1996). "Competition and regulation in the taxi industry." *Journal of Public Economics* 59: 1-15.
- Cervero, R. (1997). *Paratransit in America: Redefining Mass Transportation*. Westport, CT: Praeger Publishers.
- Chang, H., Y. Tai, and J. Y. Hsu (2010). "Context-aware taxi demand hotspots prediction." *International Journal of Business Intelligence and Data Mining* 5(1): 3-18.

- City of Boston (200). *Boston Transportation Fact Book and Neighborhood Profiles*. Boston, MA.
- CMT FleetNet. <<https://portal.cmtnyc.com>>. Accessed May 12, 2011.
- Design Trust for Public Space (2007). *TAXI 07: ROADS FORWARD*. New York: New York City Taxi and Limousine Commission.
- Douglas, G. W. (1972). "Price Regulation and Optimal Service Standards: The Taxicab Industry." *Journal of Transport Economics and Policy* 20: 116-127.
- FareInvestor. <www.fareinvestor.com >. Accessed May 18, 2011.
- Frankena, M. W. and P. A. Pautler (1984). "An Economic Analysis of Taxicab Regulation." Washington, DC: Bureau of Economics, Federal Trade Commission.
- Gilbert, G. and R. E. Samuels (1982). *The Taxicab: An Urban Transportation Survivor*. Chapel Hill, NC: University of North Carolina Press.
- Jackson, K. T. (1985). *Crabgrass Frontier*. New York: Oxford University Press.
- Koehler, B. (2004). *Regulating Supply in Taxi Markets*. Master's Dissertation, Department of Economics, City University London.
- Liu, L., C. Andris, A. Biderman, and C. Ratti (2009). "Uncovering Taxi Driver's Mobility Intelligence through His Trace." In *Movement-Aware Applications for Sustainable Mobility: Technologies and Approaches*, 105-120.
- Massachusetts Bay Transportation Authority (2009). *MBTA Ridership and Service Statistics ("The Blue Book"): Twelfth Edition*. Boston, MA.
- MassGIS. <www.mass.gov/mgis>. Accessed May 18, 2011.
- Matsushima, K. and K. Kobayashi (2010). "Spatial equilibrium of taxi spot markets and social welfare." Lisbon: Proc. of the 12th WCTR.
- Mayor's Office of Transportation (1978). *Boston Taxi Study: Final Report*. Boston, MA.
- Meyer, J. R., J. F. Kain, and M. Wohl (1965). *The Urban Transportation Problem*.

Cambridge, MA: Harvard University Press.

MIT Geodata Repository. Accessed May 18, 2011.

New York City Taxi and Limousine Commission (2011). *Taxi of Tomorrow Survey Results*. New York.

Phithakkitnukoon, S., M. Veloso, C. Bento, A. Biderman, and C. Ratti (2010). "Taxi-Aware Map: Identifying and Predicting Vacant Taxis in the City."

Schaller, B. (1999). "Elasticities for taxicab fares and service availability." *Transportation* 26: 283-297.

Schaller, B. (2007). "Entry Controls in Taxi Regulation."

Schaller Consulting (2006). *The New York City Taxicab Fact Book*. New York.

Schroeter, J. R. (1983). "A model of taxi service under fare structure and fleet size regulation." *Bell Journal of Economics* 14(1): 81-96.

Sigelman, L. and L. Zeng (1999). "Analyzing Censored and Sample-Selected Data with Tobit and Heckit Models." *Political Analysis* 8(2): 167-182.

Small, K. A. and C. Winston (1999). "The Demand for Transportation: Models and Applications." In *Essays in Transportation Economics and Policy: A Handbook in Honor of John R. Meyer*, ed. J. Gomez-Ibanez, W. Tye, and C. Winston, 11-56. Washington, DC: Brookings Institution Press.

Teal, R. F. and M. Berglund (1987). "The Impacts of Taxicab Deregulation in the USA." *Journal of Transport Economics and Policy* 21(1): 37-56.

Teal, R. F., J. V. Marks, and R. E. Goodhue (1979). "Subsidized Shared-Ride Taxi Services."

Thomson, J. M. (1977). *Great Cities and Their Traffic*. London: Victor Gollancz Ltd.

Tsamboulas, D. A. and A. Nikoleris (2008). "Passengers' willingness to pay for airport ground access time savings." *Transportation Research Part A* 42: 1274-1282.

U.S. Census. (2000).

Verifone eFleet. <www.verifone.com>. Accessed May 12, 2011.

Weather Underground. <www.wunderground.com> Accessed May 18, 2011.

Webster, A. L., E. Weiner, and J. D. Wells (1974). "The Role of Taxicabs in Urban Transportation." Washington, DC: Office of Transportation Planning Analysis, US Department of Transportation.

Yamamoto, K., K. Uesugi, and T. Watanabe (2008). "Adaptive Routing of Cruising Taxis by Mutual Exchange of Pathways." In KES 2008, Part II, LNAI 5178, eds. I. Lovrek, R. J. Howlett, and L. C. Jain, 559-566. Berlin: Springer-Verlag.

Yang, H., C. S. Fung, K. I. Wong, and S. C. Wong (2010). "Nonlinear pricing of taxi services." *Transportation Research Part A* 44: 337-348.

Yang, H., S. C. Wong, and K. I. Wong (2002). "Demand–supply equilibrium of taxi services in a network under competition and regulation." *Transportation Research Part B* 36: 799-819.

Ziebart, B. D., A. L. Maas, A. K. Dey, and J. A. Bagnell (2008). "Navigate Like a Cabbie: Probabilistic Reasoning from Observed Context-Aware Behavior." In *UbiComp 2008: Proceedings of the 10th International Conference on Ubiquitous Computing*, 322–331. New York: ACM.

VIII. APPENDIX

A. Incidence rate ratios for Poisson trip count models

	Incidence Rate Ratio			
	AM Peak	PM Peak	Evening	Overnight
Land area (km ²)	2.86	5.22	3.54	2.74
Open space (km ²)	0.60	0.31	0.63	0.53
Airport (dummy)	0.18	0.01	0.03	0.04
Commercial land use (%)	4.98	6.95	4.94	6.57
Non-res. building vol. (1,000,000 m ³)	1.04	1.04	1.03	1.04
Zero-car households (%)	0.71	0.77	0.97	1.06
Population (1,000)	1.55	1.35	1.16	1.42
Med. household income (\$10,000)	1.06	1.03	1.00	0.97
Bus routes	1.04	1.05	1.05	1.05
Major bus routes	0.85	0.95	0.92	0.94
Distance from Blue Line (log)	1.13	1.03	0.97	1.11
Distance from Green Line (log)	0.87	0.80	0.76	0.83
Distance from Red Line (log)	1.02	1.09	1.14	1.00
Distance from Orange Line (log)	0.99	1.04	1.07	1.02
Silver Line (dummy)	1.05	1.14	1.21	1.16
Distance from center (km)	0.70	0.65	0.66	0.80
Intersections (100 per km ²)	0.75	0.71	0.80	0.85
Class 1 road (dummy)	1.24	0.79	1.09	0.99
Class 2-4 road (km)	1.02	1.10	1.10	1.02

B. Correlation matrix of dependent variables

	Land area	Open space	Open space %	Comm. LU %	Non-res. bldg. vol.	Zero-car HH %	Population	Pop. density	Bus routes	Major bus routes	Blue Line dist.	Green Line dist.	Red Line dist.	Orange Line dist.	Silver Line	Int. density	Class 1 road	Class 2-4 road	Dist. from center	Med. HH income	Logan Airport dummy	
Land area	1.00																					
Open space	0.64	1.00																				
Open space %	0.38	0.69	1.00																			
Comm. LU %	(0.08)	(0.12)	(0.13)	1.00																		
Non-res. bldg. vol.	0.34	0.08	0.09	0.37	1.00																	
Zero-car HH %	(0.11)	(0.13)	(0.07)	0.33	0.19	1.00																
Population	0.04	0.03	0.03	0.02	0.04	0.16	1.00															
Pop. density	(0.38)	(0.24)	(0.27)	0.16	(0.19)	0.44	0.30	1.00														
Bus routes	0.21	0.06	(0.00)	0.38	0.46	0.23	0.05	(0.18)	1.00													
Major bus routes	(0.14)	(0.11)	(0.05)	0.05	(0.03)	0.25	0.04	0.04	0.20	1.00												
Blue Line dist.	0.09	0.09	0.06	(0.36)	(0.25)	(0.39)	(0.10)	(0.35)	(0.25)	0.15	1.00											
Green Line dist.	0.18	0.09	(0.05)	(0.39)	(0.24)	(0.40)	(0.13)	(0.46)	(0.15)	(0.27)	0.30	1.00										
Red Line dist.	0.09	0.10	0.12	(0.23)	(0.18)	(0.19)	(0.04)	(0.11)	(0.14)	0.09	0.21	(0.03)	1.00									
Orange Line dist.	0.14	0.09	0.03	(0.30)	(0.21)	(0.37)	(0.02)	(0.27)	(0.27)	(0.24)	0.34	0.46	0.03	1.00								
Silver Line	0.01	(0.06)	(0.04)	0.26	0.25	0.22	(0.04)	0.12	0.23	0.08	(0.36)	(0.18)	(0.15)	(0.31)	1.00							
Int. density	(0.26)	(0.17)	(0.19)	0.26	(0.02)	0.22	(0.02)	0.46	0.09	0.01	(0.40)	(0.39)	(0.16)	(0.41)	0.23	1.00						
Class 1 road	0.13	(0.03)	0.02	0.31	0.27	0.18	0.01	0.02	0.43	(0.10)	(0.37)	(0.26)	(0.09)	(0.16)	0.05	0.14	1.00					
Class 2-4 road	0.75	0.34	0.20	0.13	0.50	0.07	0.02	(0.25)	0.41	(0.04)	(0.09)	(0.03)	(0.05)	(0.04)	0.13	(0.05)	0.36	1.00				
Dist. from center	0.20	0.19	0.10	(0.38)	(0.19)	(0.55)	(0.01)	(0.46)	(0.24)	(0.12)	0.63	0.49	0.23	0.50	(0.43)	(0.42)	(0.38)	(0.10)	1.00			
Med. HH income	0.02	0.02	0.07	(0.01)	(0.02)	(0.61)	(0.15)	(0.13)	(0.11)	(0.26)	(0.02)	(0.03)	0.02	0.00	0.01	0.09	0.09	(0.02)	0.09	1.00		
Airport dummy	0.66	0.04	(0.02)	(0.04)	0.19	0.10	(0.07)	(0.06)	0.09	(0.04)	(0.01)	0.03	0.03	0.03	0.11	(0.06)	0.10	0.51	(0.03)	(0.07)	1.00	

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